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PHYSICS

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ELECTIVE

B

FLUIDS AT REST

ALBERTA CORRESPONDENCE SCHOOL
ALBERTA EDUCATION

Physics 10

Elective B

FLUIDS AT REST

Distance Learning

Alberta EDUCATION

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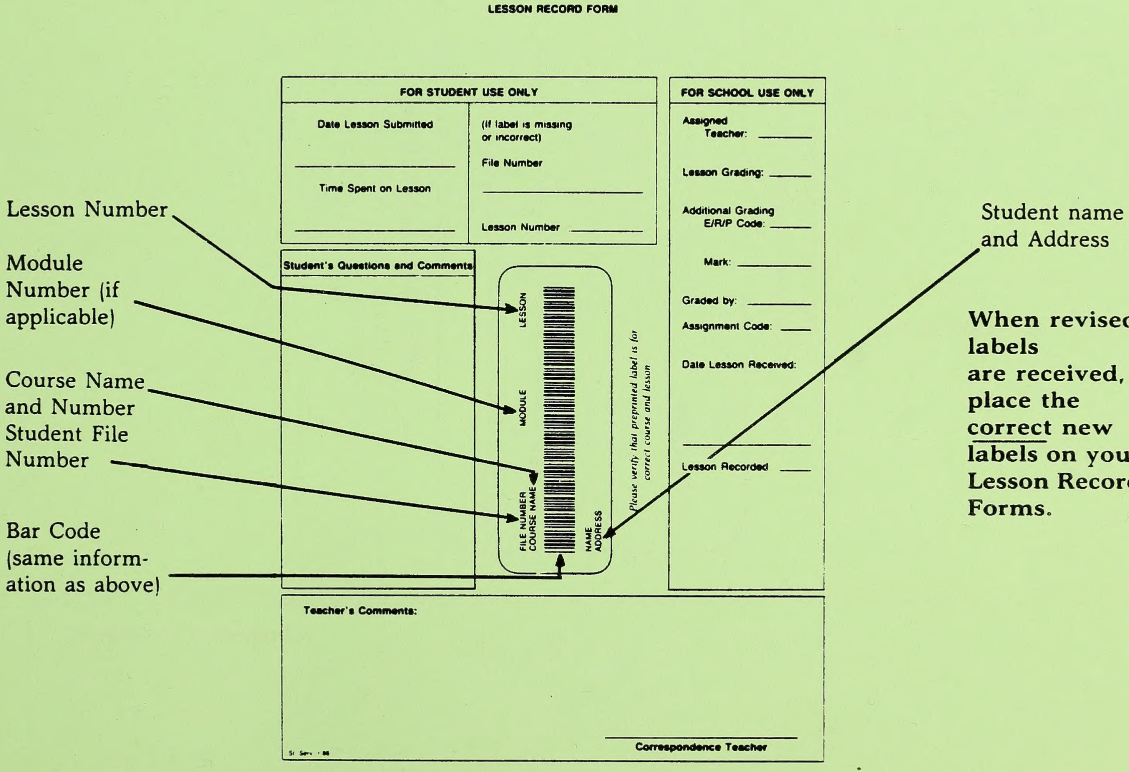
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LIQUID FORCES IN OPEN VESSELS

Probably the most familiar substance the world over is water. We are all acquainted with water as a liquid, with ice as the solid state of water and with steam as the gaseous or vapor state of water. The differences in state are due not to changes in composition but rather to changes in temperature and pressure. This lesson will concentrate mainly on the liquid form of water, and of other substances.

We shall find that there are many familiar machines which depend upon the fluidity of some liquid. For example, the hydraulic brakes on an automobile depend upon a liquid which will not easily freeze and yet will transmit the force of the foot, much magnified, to the brakes on the four wheels. Water wheels, hydraulic presses and hydraulic jacks also make use of liquids. Furthermore, ships float, anchors sink and submarines do either at the will of their commanders, in accordance with certain laws that deal with liquids. In this lesson we shall study how liquids offer a very convenient medium for the transmission of pressure.

Force and Pressure

In studying liquids, we must distinguish carefully between the terms "force" and "pressure". Force means a push or a pull. Force is expressed in newtons (N). Pressure means the push or pull per unit area of the surface acted upon. Pressure is expressed in pascals (Pa), which are newtons per square metre (N/m^2). Because of the magnitude of the pressure in most situations, the kilopascal (kPa) is the unit used for pressure.

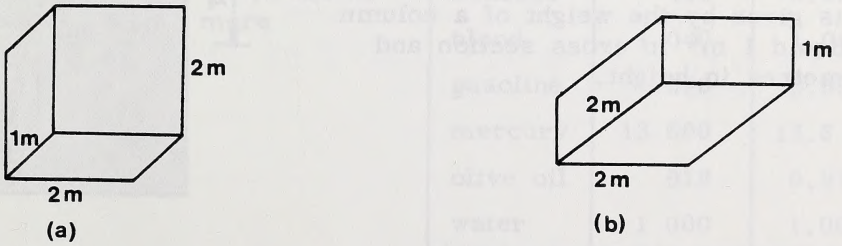
$$\text{Pressure} = \text{Force/area}$$

or

$$P = F/A$$

As an illustration of the distinction between pressure and total force, consider the two blocks in Fig. A.

Fig. A



(a) (b)

Block (a) stands on one end where the area is 2.0 m^2, while block (b) stands on one side where the area is 4.0 m^2. Weighing 1000 N, each block separately exerts the same downward force. Standing on end as in (a), the downward pressure is

$$\text{pressure} = \text{force/area} = \frac{1000\ \text{N}}{2.0\ \text{m}^2} = 500\ \text{N/m}^2 = 5.0 \times 10^2\ \text{Pa}$$
$$= 5.0 \times 10^{-1}\ \text{kPa}$$

Standing as in (b), the pressure is

$$\text{pressure} = \text{force/area} = \frac{1000\ \text{N}}{4.0\ \text{m}^2} = 250\ \text{N/m}^2 = 2.5 \times 10^2\ \text{Pa}$$
$$= 2.5 \times 10^{-1}\ \text{kPa}$$

The pressure in (a) is, therefore, twice as great as the pressure in (b) but the total downward force is the same.

To obtain force, we can also write (using pressure and area)

$$\text{Force} = \text{Pressure} \times \text{area}$$

or

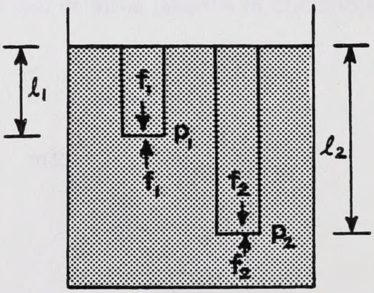
$$F = P \times A$$

Liquid Pressure

It is frequently necessary to determine the pressure at various depths within a liquid as well as the pressure on the bottom and sides of any containing vessel. The rule regarding pressure states that the magnitude of the pressure at any depth is equal to the weight of a column of liquid of unit cross-section reaching from that point to the top of the liquid.

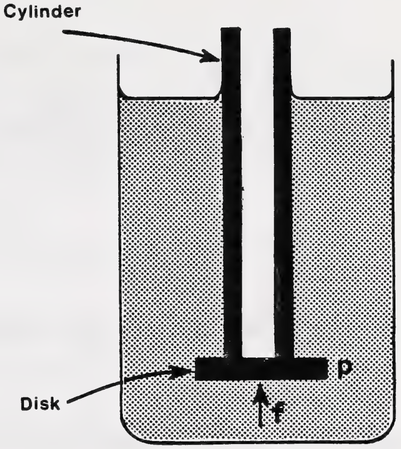
At a depth of ℓ_1, as shown in Fig. B, the pressure p_1 is given by the weight of a column of liquid 1 m^2 in cross-section and ℓ_1 metres in height. At the greater depth of ℓ_2, the pressure p_2 is given by the weight of a column of liquid 1 m^2 in cross section and ℓ_2 metres in height.

Fig. B



This can be demonstrated with a glass cylinder and a thin lightweight disk as shown in Fig. C. With water surrounding the empty cylinder the force, f, pushing up, holds the disk tightly against the end. If the cylinder is gradually filled with water, an increasing downward force is exerted on the disk. Just as the water inside reaches the level of the water outside, the disk drops from the end of the cylinder, showing that the downward force and upward force at that point and at that instant become equal. We can conclude from this experiment that the pressure at any given point in a liquid is given by the weight of the liquid above it. Moreover, we see that the pressure at one point is equal to the pressure at any other point at the same level.

Fig. C



Liquid Density

To find the weight of a column of liquid it is convenient to know the liquid density. The density of any substance or body of matter is given by the mass per unit volume. To find the density, one determines the volume of a given mass of the substance and divides that mass by the volume.

density = mass/volume

or $D = m/V$

The density of a few common materials are given in the table to the right. The most common unit of density has been the gram per cubic centimetre (g/cm^3); it is now probable that the derived unit of density, kilogram per cubic metre (kg/m^3), will become more prominent.

Material	D (kg/m^3)	D (g/cm^3)
alcohol	790	0.79
benzene	700	0.70
blood	1 040	1.04
gasoline	690	0.69
mercury	13 600	13.6
olive oil	918	0.918
water	1 000	1.000

Pressure due to a Liquid Column

The mass of any column of liquid is found from

$$m = DV$$

To find the weight of any mass, m, we multiply by a_g, the acceleration due to gravity. The weight, then, is the total downward force, F, of a liquid column, and we can write,

$$F = ma_g$$

or

$$F = DVa_g \quad (\because m = DV)$$

The volume, V, of a column of liquid is given by

$$V = hA$$

where h = the column's height, A = the column's cross-sectional area.

Substituting this in the equation above, we get

$$F = DhAa_g$$

By definition,

$$p = F/A$$

Therefore,

$$P = \frac{DhAa_g}{A}$$

$$P = Dha_g.$$

Therefore pressure due to a column of liquid is

$$\boxed{P = hDa_g}$$

where h is the height of the column, D the density of the liquid and a_g the acceleration due to gravity.

QUESTIONS

1. How is pressure defined?

2. Explain why a girl wearing spike heeled shoes can damage a floor whereas her boy friend wearing work boots and weighing almost twice as much, does not.

3. How can the pressure at any depth within a liquid be calculated?

4. Is pressure a force?

5. Why do fish that normally live at great depths in the ocean burst when quickly brought up to the surface?

6. Give an illustration to show that the same object can exert different amounts of pressure due to its weight.

7. Compare the pressure due to water at a depth of 10 m with pressure at 20 m and at 30 m.

Work through the following examples carefully and solve the problems following.

EXAMPLE 1

1. A concrete block 2.0 m wide, 3.0 m long and 1.0 m high has a mass of 1.0×10^3 kg. Find the pressure it exerts on the ground.

Given: length = 3.0 m, width = 2.0 m, height = 1.0 m
mass of block = 1000 kg

To find: pressure = ?

Solution: P = Force/area

$$\text{Force} = \text{weight} = m \times a_g = 1000 \text{ kg} \times 9.8 \text{ m/s}^2 = 9800 \text{ N}$$

$$\text{Area} = \text{length} \times \text{width} = 2.0 \text{ m} \times 3.0 \text{ m} = 6.0 \text{ m}^2$$

$$P = \frac{9800 \text{ N}}{6.0 \text{ m}^2} = 1633.3 \text{ N/m}^2 = 1.6 \times 10^3 \text{ Pa} = 1.6 \text{ kPa}$$

EXAMPLE 2

2. A block of aluminum measures 15 cm × 10 cm × 12 cm and has a mass of 4500 g. What is the density of aluminum in g/cm^3 and in kg/m^3 ?

Given: dimension of the block = 15 cm × 10 cm × 12 cm
mass of the block = 4500 g

To find: density = ?

Solution: volume of the block = 15 cm × 10 cm × 12 cm $= 1800 \text{ cm}^3$

Mass of the block = 4500 g

$$\text{density (D)} = \frac{4500 \text{ g}}{1800 \text{ cm}^3} = 2.5 \text{ g/cm}^3$$

Conversion of g/cm^3 to kg/m^3

$$1\ g = 10^{-3}\ kg$$

$$1\ cm = 10^{-2}\ m$$

$$1\ cm^3 = 10^{-6}\ m^3$$

$$\therefore\ g/cm^3 = \frac{10^{-3}\ kg}{10^{-6}\ m^3}$$

$$= 10^3\ kg/m^3.$$

You could simply remember that to change density from g/cm^3 to kg/m^3, you have to multiply by 1000: i.e. If density is 2.5 g/cm^3, it is the same as $2.5 \times 10^3\ kg/m^3$. (Note: to change density from kg/m^3 to g/cm^3, divide by 1000.)

EXAMPLE 3

3. Calculate the pressure due to a column of mercury 76 cm high. (It is called normal atmospheric pressure.)

Given: height, $h = 76\ cm = 0.76\ m$

density, $D = 1.36 \times 10^4\ kg/m^3$ (table page 3)

To find: pressure, $P = ?$

Solution: $P = hDa_g$

$$= 0.76\ m \times 1.36 \times 10^4\ kg/m^3 \times 9.80\ m/s^2$$

$$= 1.0 \times 10^5\ N/m^2$$

$$= 1.0 \times 10^5\ Pa$$

$$= 1.0 \times 10^2\ kPa$$

PROBLEMS

1. A block of wood measures 20 cm by 30 cm by 10 cm and has a mass of 4200 g. Find its density in g/cm^3 and kg/m^3.

2. What is the mass of the air present in a room measuring 4 m × 5 m × 6 m if the density of air in the room is 0.001 293 g/cm^3 ?

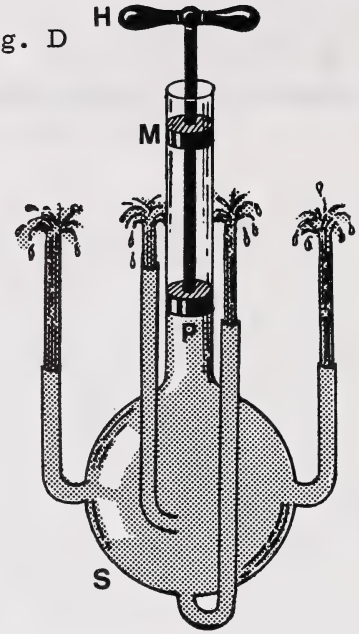
3. A rectangular tank 30.0 m wide and 40.0 m long is filled with water to a depth of 10.0 m. Find the pressure at the bottom of the tank and the total force on the bottom.

4. Find the pressure at the bottom of a tank of gasoline 12 m deep.

Pressure Acts in All Directions

If pressure is applied to a point on the liquid surface it is equally transmitted in all directions. A simple apparatus shown in Fig. D can be used to demonstrate this fact. A hollow steel ball, S, filled with water, is connected at the top by a metal tube M. If one pushes down on the handle, H, the plunger, P, forces water out of the several metal tubes leading from the sides and the bottom of the ball. Equal pressure in all directions is indicated by the water jets all coming to the same height.

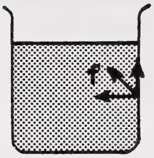
Fig. D



Pressure on a Surface

In a liquid at rest, the force exerted by the liquid upon any surface is perpendicular to the surface. At any given point, the force exerted on an element of surface is independent of the orientation of that surface. As a proof, suppose the forces were not perpendicular but at some angle to the surface (see Fig. E). Such a force could be resolved into two components, one normal and the other tangent to the surface. But, the tangent component cannot exist, for if it did, the wall would exert an equal and opposite force on the liquid and the liquid will move. Because the liquid is assumed to be at rest, the force, f, must be normal.

Fig. E



Pressure is Proportional to the Depth

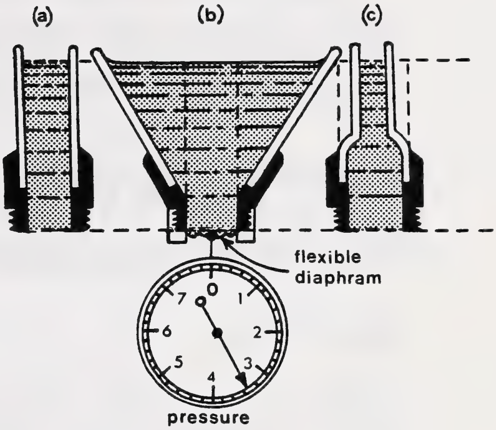
If you recall the expression for the pressure due to a liquid column derived on page 4 of the lesson, you know

$$P = hDa_g$$

'D' the density of the liquid and 'a_g' the acceleration due to gravity are both constant, for a particular liquid. Therefore, for a particular liquid, the pressure only depends on 'h', the height of the liquid column. The greater the 'h' is, the greater the pressure will be. In other words, the pressure exerted by a liquid column is independent of the size and the shape of the vessel containing the liquid.

A simple apparatus can be used to demonstrate this fact. The vessels shown in Fig. F are known as Pascal's vases. Three glass vessels of different shapes but the same height have screw-in metal bases that fit into the same pressure meter shown at the lower centre. The three vases are inserted one after the other and filled with water to the same height. Even though the amount of water is greatly different in each vase, the pressure, as measured by the meter, is the same.

Fig. F



Liquids also Exert Pressure Sideways

We all know that if a hole is bored in the side of a barrel of water, the water will spurt out. This proves that before the hole was bored the liquid was pressing against that bit of the side of the barrel. Liquids, then, exert a sideways pressure because of their weight, as well as a downward pressure. The sideways pressure of a liquid increases with the depth of the liquid just like the downward pressure.

Calculation of Sideways Force

The total push of a liquid against the walls of the containing vessel can be calculated easily if you remember that the sideways pressure increases gradually from zero at the surface to its maximum value at the bottom. We have already seen that the pressure at the bottom is hDa_g. Therefore,

$$\text{average sideways pressure} = \frac{\text{pressure at surface} + \text{pressure at bottom}}{2}$$

$$= \frac{0 + hDa_g}{2}$$

$$\boxed{P_{\text{avg.}} = \tfrac{1}{2}hDa_g}$$

This is the pressure half-way down. Therefore the average sideways pressure is equal to the pressure halfway down.

Force sideways = $\frac{1}{2}hDa_g \times A$, where A is the area of the side.

Pressure is Important in Water Storage

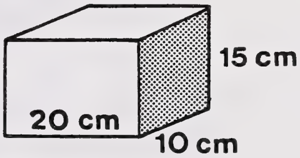
Any device intended for use underwater must be designed to withstand water pressure. The greater the depth of water involved, the greater is the pressure. A good example of this is the use of dams; they are made very thick at the bottom where the pressure is the greatest, and thinner toward the top.

When a water faucet is opened, the water does not simply fall out. It is forced out by the pressure inside the system. One way to provide this pressure is to store water in the tank above the point where it is being used. You will learn more about this in Lesson 12B.

EXAMPLE 4

A box 0.10 m wide, 0.20 m long, and 15 cm deep, is filled with water. What is the total force tending to push out the end of the box?

Given: width = 0.10 m, length = 0.20 m
depth = 15 cm



To find: force sideways = ?

Solution: Area of the end = 0.15 m × 0.10 m = $0.015\ \text{m}^2$

$$\text{Force sideways} = \tfrac{1}{2}hDa_gA$$

$$= \tfrac{1}{2} \times 0.15\ \text{m} \times 1000\ \frac{\text{kg}}{\text{m}^3} \times 9.8\ \text{m/s}^2 \times 0.015\ \text{m}^2$$

$$= 11.025\ \text{N}$$

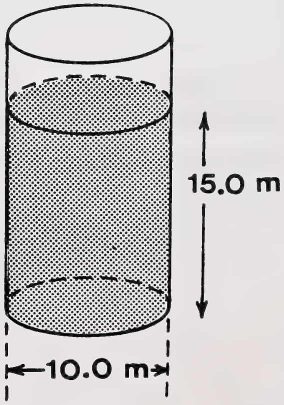
$$= 11\ \text{N}$$

EXAMPLE 5

A cylindrical water tank with a diameter of 10.0 m is filled to a depth of 15.0 m. What is the pressure on the bottom? What is total force on the bottom? What is the total force on the sides?

Given: diameter of tank = 10.0 m
depth of water = 15.0 m

To find: pressure on the bottom;
force on the bottom; and
force on the sides



Solution:

$$\text{Pressure on the bottom, } P = hDa_g$$

$$= 15.0 \text{ m} \times 1000 \frac{\text{kg}}{\text{m}^3} \times 9.8 \text{ m/s}^2$$

$$= 1.47 \times 10^5 \text{ N/m}^2$$

$$= 1.5 \times 10^5 \text{ Pa}$$

$$= 1.5 \times 10^2 \text{ kPa}$$

Total force on the bottom will be pressure times area of the bottom.

$$\text{Area of the bottom} = \pi r^2$$

$$= 3.14 \times (5.0 \text{ m})^2$$

$$= 78.5 \text{ m}^2$$

$$\text{Force} = P \times A$$

$$= 1.5 \times 10^5 \frac{\text{N}}{\text{m}^2} \times 78.5 \text{ m}^2$$

$$= 1.2 \times 10^7 \text{ N}$$

To find the total force on the sides, find the average pressure on the sides and the area of the sides.

Average pressure on the sides is the pressure half way down; i.e.

$$P_{\text{avg.}} = \tfrac{1}{2}hDa_g$$

$$= \tfrac{1}{2} \times 15.0 \text{ m} \times 1000 \frac{\text{kg}}{\text{m}^3} \times 9.8 \text{ m/s}^2$$

$$= 7.35 \times 10^4 \text{ N/m}^2$$

$$= 7.4 \times 10^4 \text{ Pa}$$

$$= 74 \text{ kPa}$$

$$\text{Area of the sides} = \pi hd$$

$$= 3.14 \times 15.0 \text{ m} \times 10.0 \text{ m}$$

$$= 471 \text{ m}^2$$

$$\text{Force on the sides} = P_{\text{avg.}} \times \text{Area of the sides}$$

$$= 7.4 \times 10^4 \frac{\text{N}}{\text{m}^2} \times 471 \text{ m}^2$$

$$= 3.5 \times 10^7 \text{ N}$$

QUESTIONS

1. (a) What do Pascal's vases demonstrate?

____

____

____

(b) How can you explain the equal pressure exerted on the bottom surface area of each vase?

____

____

____

2. Explain why liquids at rest exert a force that is normal to any surface in contact with the liquid.

____

____

____

____

3. How does the pressure on an immersed object depend upon

(a) its depth? ____________________________

____

(b) its area? ____________________________

____

(c) the density of the liquid? ____________________

____

4. How is the average sideways pressure related to the pressure at the bottom of a liquid column?

5. Do liquids exert pressure sideways? Give reasons to support your answer.

6. Is the wall of a dam of uniform thickness? If not, why not?

PROBLEMS

1. At what depth below the surface of water will the pressure due to water alone be 1.5 atmospheres? (1 atmosphere = 1.0×10^5 Pa)

2. A rectangular tank 6.0 m long, 4.0 m broad and 2.0 m deep is full of water. Find the magnitude of the total force on the bottom, on one broadside and on one endside.

3. A cylindrical water tank with a diameter of 6.0 m is filled to a depth of 12.0 m. What is the pressure on the bottom? What is the total force on the bottom? What is the total force on the sides?

Calculation of Total Pressure

So far we were concerned with pressures produced by liquids, neglecting the pressure produced by the weight of the atmosphere above. To determine total pressure or absolute pressure, we must add the atmospheric pressure to the liquid pressure. Thus if the barometric pressure was 76 cm of mercury or 1.0×10^2 kPa and liquid pressure was 0.5×10^2 kPa, then the total pressure is 1.5×10^2 kPa; i.e.

$$P_{Total} = P_{Liquid} + P_{atmosphere}$$

Why do Liquids Rise in Tubes?

Whenever we sip a soft drink through a straw we show that a liquid rises in a tube. The soft drink rises in the straw because it is pushed up by the pressure of the atmosphere on the surface of the liquid outside the straw. The pressure of the liquid within the straw is reduced by suction.

More than three centuries ago, the Duke of Tuscany had a deep well dug and found that any available pump could lift the water to a limited height. Evangelista Torricelli investigated this limit and found it to be 10.36 m under ideal conditions, although in practice a lift pump can raise water only about 8.5 m because of inadequate seals. Torricelli, a friend and follower of Galileo, was greatly interested in the reason for this limit and asked Galileo. Galileo replied jestingly that probably nature's abhorrence of a vacuum did not extend beyond 10.36 m. This difficulty stimulated Torricelli to further endeavors, which resulted in the invention of the barometer (pressure measuring device).

Torricelli wondered whether nature's abhorrence of a vacuum depended upon the density of the liquid used. He thought that mercury, being 13.6 times as dense as water, might be pumped to 1/13.6 of the height of water. He filled a long glass tube with mercury, closed the open end with his thumb and inverting the tube, placed the end thus closed under the surface of a dish of mercury. (Fig. G) When he removed his thumb, mercury escaped from the tube until the upper surface of mercury in the tube was about 76 cm above the level of the mercury in the dish. Note that 10.36 m, the height of water, is approximately 13.6 times as great as 76 cm, the height of mercury. In later experiments, it was shown that the vertical height of the column is independent of the width of the tube or its tilt.

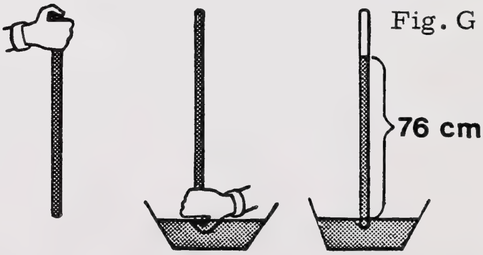
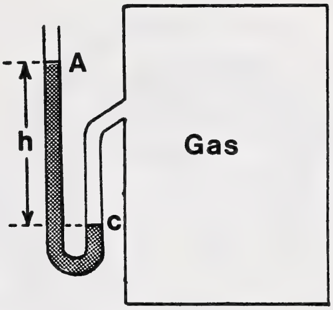


Fig. G

Torricelli's experiments proved that the height to which a liquid will rise in an exhausted tube depends upon the pressure of the air on the surface of the liquid outside the tube.

Fig. H



The Open-Tube Manometer

The pressure of an enclosed mass of a gas may be measured by an open-tube manometer as shown in Fig. H. This consists of a U-shaped tube containing a liquid of known density (D). One end of the tube is connected to the gas container, while the other end is open to the atmosphere. The pressure at A in the open-tube is the atmospheric pressure, P_A. At C, there is an additional pressure, hDa_g, due to the weight of the liquid. The total pressure P is the sum of the two.

$$P_{Total} = P_A + hDa_g$$

This type of manometer is useful in measuring small differences in pressure. If you use a liquid of lower density, h will be large and easy to measure.

EXAMPLE 6

The reading of an open-tube water manometer connected to a gas system is 20.0 cm of water, and the atmospheric pressure is 75 cm of mercury. What is the total pressure?

Given: $h_{water} = 20.0 \text{ cm} = 0.200 \text{ m}$

$h_{mercury} = 75 \text{ cm} = 0.75 \text{ m}$

To find: $P_{Total} = ?$

Solution: $P_{water} = hDa_g$

$$= 0.200 \text{ m} \times 1000 \frac{\text{kg}}{\text{m}^3} \times 9.8 \text{ m/s}^2$$

$$= 1960 \text{ N/m}^2$$

$$= 1960 \text{ Pa}$$

$$= 1.96 \text{ kPa}$$

$$
\begin{aligned}
P_{\text{atmosphere}} &= hDa_g \\
&= 0.75\ \text{m} \times 1.36 \times 10^4\ \text{kg/m}^3 \times 9.8\ \text{m/s}^2 \\
&= 9.996 \times 10^4\ \text{N/m}^2 \\
&= 9.996 \times 10^4\ \text{Pa} \\
&= 9.996 \times 10^1\ \text{kPa}
\end{aligned}
$$

$$
\begin{aligned}
P_{\text{Total}} &= P_{\text{atmosphere}} + P_{\text{water}} \\
&= 9.996 \times 10^1\ \text{kPa} + 1.96\ \text{kPa} \\
&= 101.92\ \text{kPa} \\
&= 1.0 \times 10^2\ \text{kPa.}
\end{aligned}
$$

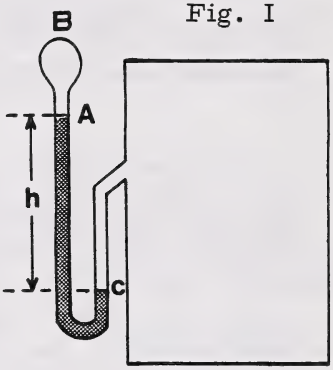


Fig. I

The Closed-Tube Manometer

The open-tube manometer is inconvenient because the atmospheric pressure, being variable, must be determined and the total pressure is then found. The closed-tube manometer is preferable because the difference in the liquid levels indicates the correct pressure directly. In the closed-tube manometer the end, B, is sealed and the space above the column of liquid is evacuated to a very high degree (Fig. I). The liquid column, h, is supported entirely by the pressure of the gas in the tank. Thus the total pressure of the gas is equal to that produced by this column of liquid; i.e.

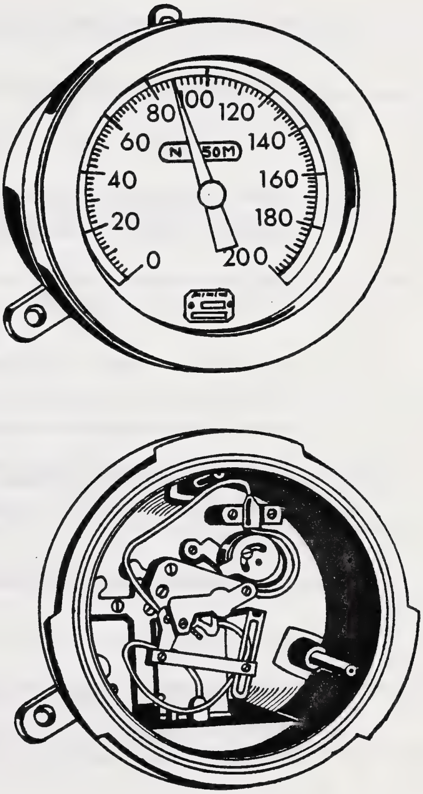
$$P = hDa_g$$

The liquid most often used in this type of manometer is mercury because mercury has a relatively great density, so 'h' does not become too large.

The Bourdon Gauge

A pressure gauge commonly used is shown in Fig. J. A flattened, thin-walled, metal tube is bent so as to lie along the arc of a circle. When the tube is evacuated, the atmospheric pressure causes the flattened walls to curl into a smaller circle. When the pressure of the enclosed air is greater than the atmospheric pressure, the walls bulge out and the tube tends to straighten out. A gear attached to the tube rotates the pointer so that its position measures the pressure. The Bourdon gauge indicates the excess of gas pressure above that of the atmosphere. Thus the total pressure is this value plus the atmospheric pressure. Some pressure gauges for measuring automobile tire pressure are of this kind.

Fig. J



QUESTIONS

1. Why does water rise in an evacuated tube?

2. How should the reading of a mercury barometer with a large bore compare with one having a small bore? Why?

3. If a tire gauge reads 2.0×10^2 kPa, what is the total pressure inside the tire? (atmospheric pressure = 1.0×10^2 kPa)

4. Why can the water level in a tube be raised up to a height of approximately 10.36 m while the level of mercury can be raised to only approximately 76 cm?

5. What is the disadvantage of using an open-tube manometer?

6. What liquid should be used in the open-tube manometer if the pressure of the inside gas is not very much different from the atmospheric pressure? Why?

7. What liquid is commonly used in closed-tube manometers and why?

____

____

____

8. What fluid is used in a Bourdon gauge?

____

____

9. How is pressure read on a Bourdon gauge?

____

____

____

10. How would you determine the absolute pressure in an automobile tire?

____

____

Lesson Summary

In this lesson, you have learned the following concepts:

Force is a push or pull and pressure is force per unit area : i.e.

$$P = F/A$$

Density of a substance is mass per unit volume or

$$D = m/V$$

Pressure at the bottom of a liquid column is given by the expression

$$P = hDa_g$$

where h is the height of the liquid column, D the density of liquid and a_g, the acceleration due to gravity.

Liquids also exert sideways pressure and the average sideways pressure is equal to the pressure half way down : i.e.

$$P_{avg.} = \frac{1}{2}hDa_g$$

The pressure acting on a surface is always perpendicular to the surface, and pressure at a point in a liquid is equal in all directions.

The closed-tube manometer is convenient to use because it gives the total pressure.

The open-tube manometer and the Bourdon gauge give the pressure due to the gas only and to find the total pressure, you must add atmospheric pressure to the liquid pressure : i.e.

$$P_{Total} = P_{atmosphere} + P_{Liquid}$$

End of Lesson 10B

LESSON RECORD FORM

1260 Physics 10 - Elective B
Revised 10/90

FOR STUDENT USE ONLY

Date Lesson Submitted ____________________

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or incorrect)

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Lesson Number ____________

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1. BEFORE MAILING YOUR LESSONS, PLEASE SEE THAT:

(1) All pages are numbered and in order, and no paper clips or staples are used.
(2) All exercises are completed. If not, explain why.
(3) Your work has been re-read to ensure accuracy in spelling and lesson details.
(4) The Lesson Record Form is filled out and the correct lesson label is attached.
(5) This mailing sheet is placed on the lesson.

2. POSTAGE REGULATIONS

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Send all letters in a separate envelope.

3. POSTAGE RATES

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Take your lesson to the Post Office and have it weighed. Attach sufficient postage and a green first-class sticker to the front of the envelope, and seal the envelope. Correspondence lessons will travel faster if first-class postage is used.

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BUOYANCY AND ARCHIMEDES' PRINCIPLE

Archimedes and a Crown

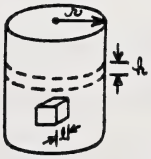
Suppose you were given the following problem. A king has had a crown made of gold. The crown is delivered to him, and he is assured by the goldsmith that the crown is pure gold. However, he knows that sometimes goldsmiths have not been completely honest, and have mixed a particular weight of silver with the gold (after having removed an equal weight of gold) used to make a crown. The total weight of the crown is equal to the weight of gold provided originally, so how can the purity of the gold of the crown be tested without destroying or damaging the crown?

According to legend, Archimedes (287 B.C. to 212 B.C.) was asked by King Hieron of Syracuse to solve such a problem. While pondering the problem, he went to one of the public baths that were common at that time. As he was settling into the water, he noticed that the water level rose, and some water spilled over the edges. Suddenly he rose, and shouting "Eureka Eureka " he ran, unclothed, into the streets. (Eureka means I have found it). What made Archimedes so excited? What did he see that gave him a way of solving the problem?

You probably have noticed that when you get in a bathtub half-filled with water, the water level goes up as more of your body is submerged. This can be illustrated in a simple way by doing the following experiment. Fill a cup or glass right to the top with water and put it in a saucer. Get about five coins (such as nickels or quarters) and tape them together. Gently put the coins in the water. What happens to the water in the glass or cup?

Some of the water over-flows; what happens is that the coins "push aside" some of the water. When this happens, the water level increases; but the glass (or cup) was full, so some of the water had to flow over the top of the container.

Of course, most people know that when you add more material to a full container of water, the water will over-flow. In order to deal with the problem of the crown, it is necessary to use some other ideas as well. One of these ideas is that when an object is completely under water, it must push aside a volume of water that is equal to its own volume. Remember that volume is the amount of space that a body takes up. When a body sinks under water in a container of water, it takes up a space that is equal to its volume, and in order to do this, it must push aside an equal volume of water. Thus the level of water in the container can be seen to increase an amount 'h' when a solid cube is submerged in it. The volume of the cube equals the volume of water displaced.



CUBE: $V_c = l^3$

Volume of Water Displaced: $V_w = \pi r^2 h$

$V_w = V_c$

$\pi r^2 h = l^3$

Another idea that we need concerns the fact that equal masses or equal weights of different substances will not have the same volume. For example, 1 kg of lead will be smaller in volume than 1 kg of wood. Also, 1 kg of gold has a smaller volume than 1 kg of silver. We sometimes describe this by saying that lead is denser than wood, or gold is denser than silver. Archimedes probably knew that gold was denser than silver, and combining this with the idea that water can be displaced by a solid submerged in it, he may have suddenly realized how he could test the crown's purity without destroying it. Can you guess how he could have tested it? If you think you can, write down your guess below then check the next page and see how it compares with the guess printed there.

A guess as to how Archimedes might have done it

Reasoning

If you take two crowns having the same mass or the same weight, one made of pure silver and one made of pure gold, you can find their volumes by placing them in two full containers of water and measuring the amount of water that overflows from each container. If this is done, you will find that the silver crown will have a greater volume than the gold crown (since silver is not as dense as gold). Now, if you have a third crown that is partly silver and partly gold but that has the same mass as the other two crowns, you will find that its volume will be greater than that of the pure gold crown, but less than that of the pure silver crown.

We can do this with any shape of crown as long as the weights are the same. In fact, we do not have to use crowns; we can use pieces of gold and silver (or silver and gold mixed together) of any shape, as long as their weights (or masses) are the same.

Testing

Now, to test the actual crown, we must obtain an amount of pure gold that is equal in mass or weight to that of the crown. Place the crown and the piece of pure gold in two filled containers of water, and find their volumes by measuring the amount of overflow water. If the volumes are the same, then the crown is pure gold. If the volumes are different, then the crown is not pure gold (and the goldsmith has tried to cheat the king).

The legend does not say whether or not the crown was pure gold, nor whether or not Archimedes actually made such a test of the royal crown. However, from books that are believed to have been written by Archimedes, it is known that he was aware of these ideas, and many others. In fact, it would seem likely that Archimedes was the greatest mathematician of the Ancient Greeks, and one of the greatest of human history.

Density and Relative Density

When we say that lead is denser than wood, or that gold is denser than silver, we are making rough comparisons between two different materials. A way to make these comparisons more than just "rough" is to use the accepted values for density. However, before we do that, we should have a definite idea of what is meant by the term density. See the following definiton.

Density is defined as the mass per unit volume of a substance.

This definition gives us a formula that lets us put the idea of density into a mathematical form, as shown by the following.

$$D = \frac{m}{V}$$

where D = density (in kg/m^3)
m = mass (in kg)
V = volume (in m^3)

Note that the "unit volume" in this case is the m^3.

Some values for the densities of various substances appear in Table 1.

Table 1 Densities of Some Substances

Substance	Density (kg/m^3)	Relative Density
Water (l)	1.00×10^3	1.00
Lead (s)	1.13×10^4	11.3
Gold (s)	1.93×10^4	19.3
Silver (s)	1.05×10^4	10.5
Mercury (l)	1.36×10^4	13.6
Copper (s)	8.93×10^3	8.93
Iron (s)	7.86×10^3	7.86
Nickel (s)	8.90×10^3	8.90
Uranium (s)	1.89×10^4	18.9
Zinc (s)	7.14×10^3	7.14
Gasoline (l)	6.6×10^2 to 6.9×10^2	6.6×10^{-1} to 6.9×10^{-1}
Granite (s)	2.60×10^3 to 2.76×10^3	2.60 to 2.76
Pine wood (s)	6.1×10^2 to 7.5×10^2	6.1×10^{-1} to 7.5×10^{-1}
Oak wood (s)	7.7×10^2	7.7×10^{-1}
Fir wood (s)	5.9×10^2	5.9×10^{-1}
Glass (s)	2.0×10^3 to 2.24×10^3	2.0 to 2.24
Stainless Steel (s)	7.75×10^3	7.75
Aluminum (s)	2.70×10^3	2.70

Note that the letters (s) and (l) stand for solid and liquid, respectively. Many of the materials in Table 1 can have different forms (solid, liquid, gas), and in those different forms, their densities would be different from those given in Table 1. Also, note that some of the substances (granite, woods, glass) have ranges of values for their densities. This is so because these substances have different compositions (they are made of different materials in varying proportions).

In order to compare the densities of substances, the idea of relative density is used.

> Relative density is defined as the ratio of the density of a substance to the density of water.

This definition can be put into mathematical form, as shown by the following formula.

$$\boxed{d_R = \frac{D_S}{D_W}}$$

where d_R = relative density (no units)
D_S = density of a substance (in kg/m^3)
D_W = density of water (in kg/m^3)

Notice that because D_S and D_W have the same units (kg/m^3), the units cancel, and relative density, d_R, has no units. (In some books, the term specific gravity is used; specific gravity is the same as relative density.)

Because the density of water is 1.00×10^3 kg/m^3, to find the relative density of any substance which has a known density it is necessary to divide by 1.00×10^3 kg/m^3. This is illustrated for silver and gold in the following example.

EXAMPLE 1

What are the relative densities of gold and silver?

Given: Density of gold $= 1.93 \times 10^4$ kg/m^3
Density of silver $= 1.05 \times 10^4$ kg/m^3

Unknown: Relative densities of gold and silver

Solution:

Gold	Silver
$d_R = \dfrac{\text{D of gold}}{D_W}$	$d_R = \dfrac{\text{D of silver}}{D_W}$
$= \dfrac{1.93 \times 10^4 \text{ kg/m}^3}{1.00 \times 10^3 \text{ kg/m}^3}$	$= \dfrac{1.05 \times 10^4 \text{ kg/m}^3}{1.00 \times 10^3 \text{ kg/m}^3}$
$= 19.3$	$= 10.5$

The relative density of gold is 19.3 and the relative density of silver is 10.5.

The last column of Table 1 gives the relative densities of the substances listed there.

Do the following exercises and send them in for correction.

QUESTIONS

1. (a) Calculate the density of a solid body having a mass of 38.5 kg and a volume of 5.0×10^{-2} m^3.

(b) From Table 1, of which material is the body made?

____

(c) What is the relative density of the body?

____

2. Which would have a larger volume, 1 kg of stainless steel, or 1 kg of aluminum? Explain why.

____

Buoyancy

It is observed often that the weight of a body in water seems to be less than its weight in air. For example, a large rock in water may be lifted by one person. However, when the rock is on the ground in the air, the person may not be able to lift the rock. Also, a block of wood may actually resist significantly any attempt to submerge it completely, and will rise to the surface of the water when released (suggesting that a force opposite to the weight and greater than the weight of the wood acts when it is underwater). This effect of the weight of a body underwater seeming to be less than its weight in air is called buoyancy. More generally, buoyancy is the decrease in weight of a body in any fluid (not just water).

When a body floats, the effect of buoyancy is such that the upward force on the body must be equal in size to the weight of the body. If this were not so, the body would sink below the surface of the water, and go to the bottom. Actually, however, there are three classes of situations that might occur when a body is put in water, and these three classes are outlined below.

1. When placed in water, the body sinks to the bottom. In this case, the weight of the body is greater than the upward force due to buoyancy, and the body sinks.

2. When placed in water, the body floats so that part of it is above the surface of the water, and part of it is below the surface of the water.

   In this case, the buoyant effect is such that the weight of the body is completely supported by the upward force. If the body is pushed down so that it is completely under water, the upward force will be greater than the weight, and the body will rise to the surface when released.

3. When placed in water, the body is underwater (at least so that its upper surface is level with the water's surface) but it does not tend to rise or sink when left undisturbed.

   In this case, the weight of the body and the upward force are balanced as long as the body remains under water. If part of the body somehow is raised above the surface of the water, its weight will be greater than the upward force, and when released the body will sink back underwater.

These three classes of situations can be observed under certain circumstances, and you may know of instances of them. For example, you probably have seen a stone fall into water and sink to the bottom. Also, you may have observed a piece of wood floating with part of it above the surface and part of it below the surface of the water. You may not have seen a case that fits in with the third class of situation, but such cases do occur. For example, a fish in an aquarium may remain motionless at one particular depth for some time.

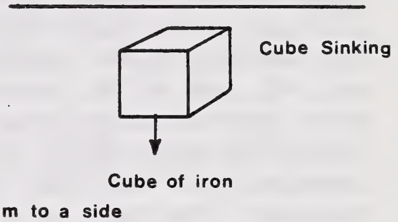
How can these kinds of behavior of bodies in water be explained? A way of explaining them uses an idea worked out by Archimedes long ago.

Archimedes' Principle

Before we find out exactly what Archimedes' Principle says, we should examine some of the situations in more detail, using what we know about balanced forces and density. Three situations are considered for the case of a body being placed in water. Note that each of these three situations can be related to the three situations in the preceding section.

1. The relative density of the body is greater than 1.00. For this body, the density must be greater than that of water. For example, the body might be made of solid iron with a density 7.86 times that of water. As you may know, if a piece of solid iron is placed in water, it will sink to the bottom.

   The calculation shown in the diagram to the right shows the values for the volume of the iron cube (V_I), the mass of the iron cube (m_I), and the weight of the cube in air. Also, the volume (V_w), mass (m_w) and weight of water displaced have been calculated. Notice that the weight of the iron is much more than the weight of the water displaced.



1.00 m to a side

$V_I = l^3 = 1.00\ m^3$

$m_I = V_I D_I = 1.00\ m^3 \times 7.86 \times 10^3\ kg/m^3$

$= 7.86 \times 10^3\ kg$

Weight of iron (in air) $= F_g = m_I a_g$

$= 7.86 \times 10^3\ kg \times 9.8\ m/s^2$

$= 7.7 \times 10^4\ N$

$V_w = 1.00\ m^3$

$m_w = V_w D_w = 1.00\ m^3 \times 1{,}00 \times 10^3\ kg/m^3 = 1.00 \times 10^3\ kg$

Weight of water displaced $= F_g = m_w a_g$

$= 1.00 \times 10^3\ kg \times 9.8\ m/s^2$

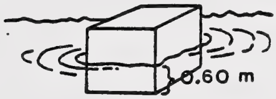
$= 9.8 \times 10^3\ N$

Weight of iron − Weight of water displaced

$= 7.7 \times 10^4\ N - 9.8 \times 10^3\ N$

$= 6.7 \times 10^4\ N$

2. The relative density of the body is less than 1.00. In the illustration to the right, a block of wood of relative density of 0.60 is shown floating in water with just 60% of its volume submerged. The calculations illustrate that when the weight of water displaced is subtracted from the weight of the block of wood, the result is zero.



Dimensions of cube of wood: 1.00 m by 1.00 m by 1.00 m

Depth of cube under water = 0.60 m

Volume of wood under water $= 1.00\ \text{m} \times 1.00\ \text{m} \times 0.60\ \text{m}$
$= 0.60\ \text{m}^3$

Total mass of wood $= 1.00\ \text{m}^3 \times 6.0 \times 10^2\ \text{kg/m}^3$
$= 6.0 \times 10^2\ \text{kg}$

Weight of wood $= 6.0 \times 10^2\ \text{kg} \times 9.8\ \text{m/s}^2$
$= 5.9 \times 10^3\ \text{N}$

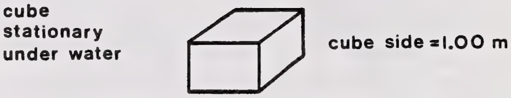
Volume of water displaced = Volume of wood under water $= 0.60\ \text{m}^3$

Mass of water displaced $= 0.60\ \text{m}^3 \times 1.00 \times 10^3\ \text{kg/m}^3$
$= 6.0 \times 10^2\ \text{kg}$

Weight of water displaced $= 6.0 \times 10^2\ \text{kg} \times 9.8\ \text{m/s}^2$
$= 5.9 \times 10^3\ \text{N}$

Weight of wood − Weight of water displaced
$= 5.9 \times 10^3\ \text{N} - 5.9 \times 10^3\ \text{N}$
$= 0$

3. The relative density of the body equals 1.00. The illustration shows a body completely submerged in water, but not sinking or rising. The calculations show that the weight of the block (in air) equals the weight of the water displaced. Thus, the difference between the two values is equal to zero.



Volume of block $= 1.00\ \text{m}^3$

Mass of block $= 1.00\ \text{m}^3 \times 1.00 \times 10^3\ \text{kg/m}^3$

$= 1.00 \times 10^3\ \text{kg}$

Weight of block $= 1.00 \times 10^3\ \text{kg} \times 9.8\ \text{m/s}^2$

$= 9.8 \times 10^3\ \text{N}$

Volume of water displaced $= 1.00\ \text{m}^3$

Mass of water displaced $= 1.00\ \text{m}^3 \times 1.00 \times 10^3\ \text{kg/m}^3$

$= 1.00 \times 10^3\ \text{kg}$

Weight of water displaced $= 1.00 \times 10^3\ \text{kg} \times 9.8\ \text{m/s}^2$

$= 9.8 \times 10^3\ \text{N}$

Weight of block $-$ Weight of water displaced

$= 9.8 \times 10^3\ \text{N} - 9.8 \times 10^3\ \text{N}$

$= 0$

In the preceding calculations, we have been applying Archimedes' Principle. The following statement gives Archimedes' Principle.

> The loss of weight of an object immersed in a fluid is equal to the weight of the fluid it displaces.

In each of the three cases considered above, the weight of the water displaced and the weight of the body in the water were compared by subtracting one from the other. For the solid iron cube, the weight of the water displaced was much less than the weight of the cube. According to Archimedes' Principle, this means that the loss of weight by the iron cube in water was smaller than the weight of the cube, and the resultant weight of the cube in water resulted in the cube sinking. For the other two cases, the weights of water displaced by the bodies were equal to the weights of the bodies. The loss of weight of a body in a fluid sometimes is called the buoyant force. The buoyant force may be calculated from the following:

$$F_B = m_f \cdot a_g$$

where F_B = buoyant force
m_f = mass of fluid displaced
a_g = acceleration of gravity

Since $$D_f = \frac{m_f}{V_f}$$

and $$m_f = V_f \cdot D_f$$

where D_f = density of fluid
V_f = volume of fluid displaced,

we have $$\boxed{F_B = V_f \cdot D_f \cdot a_g}$$

Note that V_f is not only the volume of fluid displaced, but also is the volume of the body if it is completely submerged, or is the volume of that part of the body that is submerged in the fluid.

Also, note that Archimedes' Principle refers to fluids. A fluid is a substance that flows, so Archimedes' Principle can be applied to liquids as well as gases. Study the following examples.

EXAMPLE 2

What is the buoyant force on a solid cylindrical piece of lead having a diameter of 2.00 cm and a length of 5.00 cm when it is submerged in water?

Given: $D_f = 1.00 \times 10^3 \text{ kg/m}^3$

l (length of cylinder) $= 5.00$ cm

r (radius of cylinder) $= \frac{2.00 \text{ cm}}{2} = 1.00$ cm (radius $= \frac{\text{diameter}}{2}$)

To find: F_B

Solution:

It is necessary to find the volume of the cylinder of lead (V_L).

$$\begin{aligned} V_L &= \pi r^2 l \\ &= 3.14\ (1.00 \text{ cm})^2 (5.00 \text{ cm}) \\ &= 3.14 \times 1.00 \text{ cm}^2 \times 5.00 \text{ cm} \\ &= 15.7 \text{ cm}^3 \end{aligned}$$

$$V_f = 15.7 \text{ cm}^3 \times \frac{1 \text{ m}^3}{1 \times 10^6 \text{ cm}^3} = 1.57 \times 10^{-5} \text{ m}^3$$

$$\begin{aligned} F_B &= V_f D_f a_g \\ &= 1.57 \times 10^{-5} \text{ m}^3 \times 1.00 \times 10^3 \frac{\text{kg}}{\text{m}^3} \times 9.8 \text{ m/s}^2 \\ &= 1.57 \times 10^{-2} \text{ kg} \times 9.8 \text{ m/s}^2 \\ &= 1.5 \times 10^{-1} \text{ N}. \end{aligned}$$

The buoyant force is 1.5×10^{-1} N upward.

EXAMPLE 3

A cube of nickel of 1.00 cm to a side is placed in mercury.

(a) Will the nickel float or sink?
(b) What will be the buoyant force on the nickel cube?

Given: Density of nickel = $D_N = 8.90 \times 10^3$ kg/m^3

Density of mercury = $D_M = 1.36 \times 10^4$ kg/m^3

Dimensions of cube of nickel = $1.00 \text{ cm} \times 1.00 \text{ cm} \times 1.00 \text{ cm}$

$= 1.00 \times 10^{-2} \text{ m} \times 1.00 \times 10^{-2} \text{ m} \times 1.00 \times 10^{-2} \text{ m}$

To find: (a) Will the nickel cube float or sink?
(b) F_B on the nickel cube?

Solution:

(a) The nickel will float in the mercury because nickel's density is less than the density of mercury.

(b) Since the nickel floats, the buoyant force must be equal but opposite in direction to the weight.

$$
\begin{aligned}
F_B &= \text{weight of nickel} \\
&= m_N a_g \\
&= V_N D_N a_g \\
&= (1.00 \times 10^{-2} \text{ m} \times 1.00 \times 10^{-2} \text{ m} \times 1.00 \times 10^{-2} \text{ m}) \\
&\quad (8.90 \times 10^3 \tfrac{\text{kg}}{\text{m}^3})(9.8 \text{ m/s }) \\
&= 1.00 \times 10^{-6} \text{ m}^3 \times 8.90 \times 10^3 \text{ kg/m}^3 \times 9.8 \text{ m/s} \\
&= 8.90 \times 10^{-3} \text{ kg} \times 9.8 \text{ m/s} \\
&= 8.7 \times 10^{-2} \text{ N}
\end{aligned}
$$

Buoyant force is 8.7×10^{-2} N upward.

Do the following exercises and send them in for correction.

QUESTIONS

1. (a) What is buoyancy?

   (b) What does the term "buoyant force" refer to?

2. Give a statement of Archimedes' Principle.

3. A piece of copper having a mass of 12.0 kg is placed in water. Calculate the buoyant force on the copper and the weight of the copper when in the water.

4. A piece of copper having a mass of 12.0 kg is placed in mercury. Calculate the buoyant force on the copper and the weight of the copper when in the mercury.

5. Wood with a density of 6.8×10^{2} kg/m^{3}, and a volume of 1.0×10^{-3} m^{3} is dropped on water. What volume of water would the wood displace?

6. A cubical block of fir wood having a side of 2.20×10^{-2} m is placed in water. Calculate the following things.

   (a) Volume of the block of wood.

   (b) Mass of the block of wood.

(c) Weight of the block of wood.

(d) Buoyant force on the block of wood.

(e) Depth of the block that is under water.

Measuring Relative Density

It often is important to know the relative density of substances, especially liquids, in order to see to what extent the substance is pure. There are several methods of doing this, and we shall consider four of them.

(1) Displacement

The displacement method involves immersing a solid insoluble object in water and in a liquid which has a relative density which is to be determined. The weight of the object in air is first found, and then its weight in each of the liquids is measured.

The procedure is illustrated in the diagram to the right.

In order to find the relative density of the liquid, a different form of the formula for relative density is used. The derivation of this formula is shown below.

$$d_R = \frac{D_S}{D_W} = \frac{\frac{m_S}{V_S}}{\frac{m_W}{V_W}} = \frac{m_S}{V_S} \times \frac{V_W}{m_W}$$

Because the volume of the solid put in the water and the liquid does not change,

$$V_S = V_W.$$

$$d_R = \frac{m_S}{V_S} \times \frac{V_W}{m_W} = \frac{m_S}{m_W}.$$

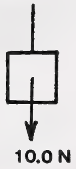
Where m_S = mass of liquid displaced

V_S = volume of liquid displaced

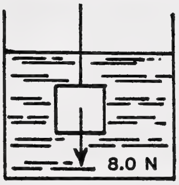
m_W = mass of water displaced

V_W = volume of water displaced

d_R = relative density of liquid

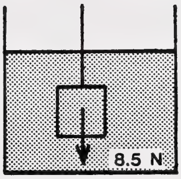


Weight in air = 10.0 N



Weight in water = 8.0 N

Loss of weight in water
= weight of water displaced
= 10.0 N − 8.0 N = 2.0 N



Weight in liquid = 8.5 N

Loss of weight in liquid
= weight of liquid displaced
= 10.0 N − 8.5 N = 1.5 N

$$d_R = \frac{\text{weight of liquid displaced}}{\text{weight of water displaced}}$$

$$= \frac{1.5\ \text{N}}{2.0\ \text{N}} = 0.75$$

Relative density of the liquid is 0.75.

Also, multiplying m_S and m_W by a_g does not change the formula, but it does convert the formula to one that uses the weights of the liquids that were displaced (or the losses of weight of the object in water and the liquid).

$$d_R = \frac{m_S\ a_g}{m_W\ a_g} = \frac{\text{weight of liquid displaced}}{\text{weight of water displaced}} = \frac{\text{loss of weight in liquid}}{\text{loss of weight in water}}$$

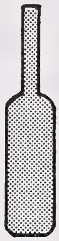
where d_R = relative density of the liquid

and the volumes of liquid displaced and water displaced are equal.

(2) Relative Density Bottle

This method involves the use of a bottle to find the relative density of a liquid. The bottle sometimes is called a relative density bottle (and sometimes is called a specific gravity bottle). The weight of the bottle is known. The bottle is filled with water and weighed. Then it is emptied, dried, filled with the liquid, and weighed. Since the volume of the bottle remains constant, the volume of the water equals the volume of the liquid. The weights of the equal volumes of water and liquid can be found by subtracting the weight of the bottle from the results of the other two weighings. Then, to calculate the relative density, the same formula as used for the displacement method can be used.

WEIGHT OF EMPTY BOTTLE = 2.0 N

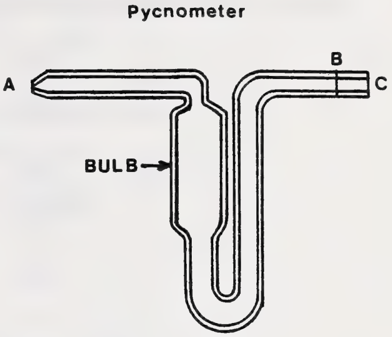


WEIGHT OF BOTTLE FULL OF WATER = 26.0 N
WEIGHT OF WATER
= 26.0 N − 2.0 N
= 24.0 N

WEIGHT OF BOTTLE FULL OF LIQUID = 20.0 N
WEIGHT OF LIQUID
= 20.0 N − 2.0 N = 18.0 N

SINCE VOLUME OF WATER EQUALS VOLUME OF LIQUID

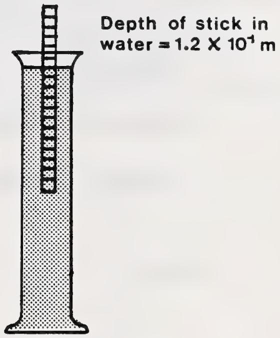
$$d_R = \frac{\text{WEIGHT OF LIQUID}}{\text{WEIGHT OF WATER}} = \frac{18.0\ \text{N}}{24.0\ \text{N}} = 0.75$$



The relative density bottle used in a laboratory may be a special design and shape. Such a bottle is called a pycnometer (also sometimes spelled pyknometer), as illustrated. While end A is put into a liquid, end C is sucked until the tubes and the bulb are filled, and the liquid reaches the mark at B. Because the tubes are quite thin, the liquid tends to remain in the pycnometer and spillage is minimized. Since the volume and weight of the pycnometer are known quite accurately, it is possible to determine the weight of the liquid in it, and then calculate an accurate value for the liquid's density and relative density. There are different designs from the one shown above for pycnometers, and some of them include thermometers, since the relative density of a liquid can change noticeably if its temperature changes.

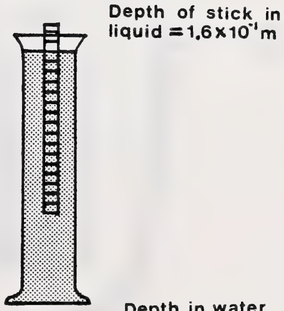
(3) Calibrated Wooden Stick

Another way of determining the relative density of a liquid is to use a calibrated wooden stick. The stick has regular divisions marked on it, giving its length. One end has some metal, such as lead, embedded in it. Also, it may be coated with wax so that it doesn't absorb liquid.



When placed in water, the stick will sink to some depth, but it will tend to remain upright in the water because of its weighted end. Since it floats, the weight of the water displaced must equal the weight of the stick.

When placed in a liquid that has a relative density different from that of water, the stick will sink to a depth different from that to which it sank in water. However, since it still floats, the weight of the liquid displaced must also equal the weight of the stick. However, the volume of liquid displaced must be different from the volume of water displaced.



$$\text{Relative density of liquid} = d_R = \frac{\text{Depth in water}}{\text{Depth in liquid}}$$

$$= \frac{1.2 \times 10^{-1}\,\text{m}}{1.6 \times 10^{-1}\,\text{m}} = 0.75$$

The expression for relative density is

$$d_R = \frac{D_S}{D_W}$$

where d_R = relative density
D_S = density of the substance
D_W = density of water

$$D_S = \frac{m_S}{V_S} \quad \text{and} \quad D_W = \frac{m_W}{V_W}$$

where m_S = mass of the substance
V_S = volume of the substance
m_W = mass of water
V_W = volume of water

When the stick displaces the water, the weight of water displaced equals the weight of the stick. Also, when it displaces the liquid, the weight of liquid displaced equals the weight of the stick. Therefore

weight of water displaced = weight of stick = weight of liquid displaced,

weight of water displaced = weight of liquid displaced

$$m_W a_g = m_S a_g$$

and

$$m_W = m_S$$

Using this in the expression for relative density, we have

$$d_R = \frac{D_S}{D_W} = \frac{\frac{m_S}{V_S}}{\frac{m_W}{V_W}} = \frac{m_S}{V_S} \times \frac{V_W}{m_W} \qquad (m_S \text{ and } m_W \text{ cancel})$$

$$d_R = \frac{V_W}{V_S}$$

The volume of water displaced = $V_W = Al_W$, and the volume of liquid displaced = $V_S = Al_S$,

where A = cross-sectional area of the stick
l_W = depth of stick in the water
l_S = depth of stick in the liquid

Therefore, $d_R = \frac{V_W}{V_S} = \frac{Al_W}{Al_S}$

$$d_R = \frac{l_W}{l_S}.$$

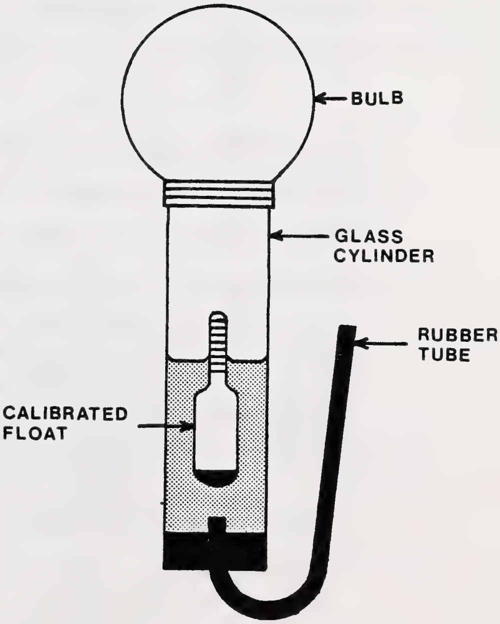
This result shows how the formula used to calculate the relative density of the liquid in the diagram can be derived.

One way to help in understanding this result is to remember that the stick would tend to sink deeper in liquids which have a lower relative density than that of water. Thus, as shown in the diagram, in the liquid having a relative density of 0.75, the depth of the stick under the liquid's surface is 1.6×10^{-1} m, while the depth of the stick under water is 1.2×10^{-1} m. If the stick were placed in a liquid having a relative density greater than that of water, it would not sink to as great a depth as it would when placed in water.

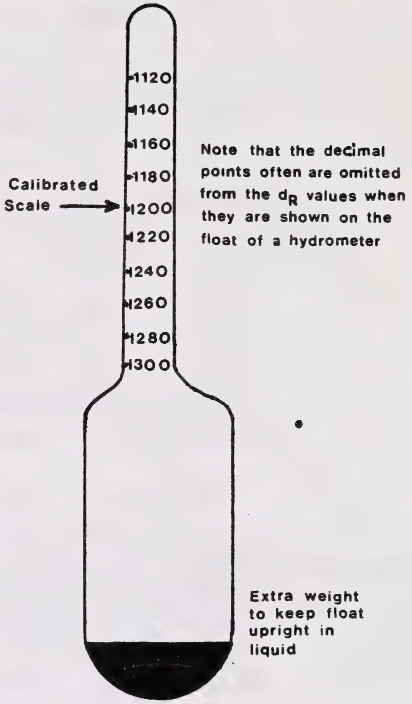
(4) The Hydrometer

The hydrometer is another instrument used to measure relative density of liquids. It uses the same principle as the calibrated wooden stick to do this, but it looks quite different from a calibrated wooden stick, as shown by the diagram to the right.

When the rubber tube is placed in a liquid and the bulb is squeezed and released, some of the liquid will come into the glass cylinder. The calibrated float will be supported by the liquid so that part of it will remain under the liquid's surface, and part of it will be above the surface.



A scale on the float with numbers marked on it can be used to read the relative density of the liquid. The calibrated float shown to the right shows some features of a float in a hydrometer. Note that the relative density values are all greater than 1.000. A hydrometer with such a float would be used to measure relative densities greater than that of pure water. For example, in the lead acid batteries used in automobiles the liquid (called the electrolyte) is a solution of water and sulfuric acid that has a relative density greater than 1.000. Measuring the relative density with a hydrometer indicates the "strength" of the electrolyte ("strength" refers to concentration — the more concentrated the acid solution is, the more acid it has, in comparison to water, and the "stronger" it is). Usually, the relative density reading should fall within a particular range at a particular temperature (such as from 1.270 to 1.300 at 25°C), if the battery is to be considered to be fully charged.



Note that the decimal points often are omitted from the d_R values when they are shown on the float of a hydrometer

Hydrometers are convenient to use because they usually have values of relative density indicated on a scale, and it is not necessary to calculate relative density using a formula. However, their designs are based upon the ideas and formula used to find relative density with a calibrated wooden stick. Also, it is important to remember that the reading from a hydrometer will vary with temperature, since the density of a liquid will change as temperature changes. Thus, if the relative density of a battery's electrolyte is measured first at 20°C and then at -20°C, the values may be significantly different (for example, it might change from 1.295 to 1.260).

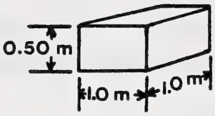
Some Applications of Buoyancy and Archimedes' Principle

There are many examples of how buoyancy and Archimedes' Principle are used to control the positions and motions of bodies in water and air. Some of these examples are described in this section.

(1) Steel Ships

If you look back to Table 1 on page 4 of this lesson, you will see that steel can have a density that is close to eight times that of water. This means that if a solid piece of steel is placed in water, it should sink. Why, then, do many steel ships float?

As you may know, steel ships are not solid pieces of steel — they have many air spaces in them. If the volume of the ship were calculated, and then used in calculation of its average density, it would be found that the average density of the ship would be less than that of water. The illustration to the right gives a calculation of average density for a hollow steel box. Note that the calculated value for the density of the box (6.2×10^2 kg/m^3) is less than that of water (1.00×10^3 kg/m^3). Hence, if the box were water-tight, it would float.

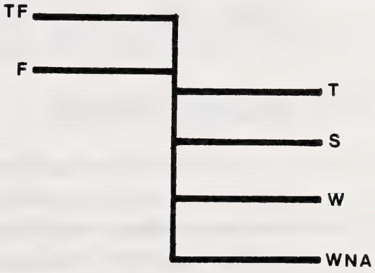


Mass of box
$m_B = 3.1 \times 10^2$ kg

$V_B = \ell wh = 1.0\ \text{m} \times 1.0\ \text{m} \times 0.50\ \text{m}$
$= 0.50\ \text{m}^3$

Density of box
$$D_B = \frac{m_B}{V_B} = \frac{3.1 \times 10^2\ \text{kg}}{0.50\ \text{m}^3} = \frac{6.2 \times 10^2\ \text{kg}}{\text{m}^3}$$

Applying this to a steel ship, its average density is less than that of water, and so it floats. Of course, ships carry loads, and it is important that the loads should not be too large. For this reason, a ship may have a special mark on its hull called the Plimsoll line. This mark shows the level which the water surface should not go beyond when the ship is loaded safely. An illustration of the Plimsoll line is shown to the right. Note that there are different kinds of water and climatic conditions which affect the maximum safe loading level for a ship.



TF - Tropical fresh water
F — Fresh water
T - Tropical salt water
S - Summer
W — Winter
WNA — Winter North Atlantic

(2) Fish

Another interesting example of the use of buoyancy is in fish. Fish usually have a relative density that is slightly greater than that of water. This means that a fish may tend to sink in water, and from the fish's point of view, that is OK. However, there are times when it is desirable for the fish to maintain a particular depth in water, and it can do this by using the swim bladder. The swim bladder is a sac which has air and other gases in it. By controlling the amount of gas in the sac, the average density of the fish can be controlled also. This allows adjustment of the density of the fish with respect to the density of the water in which the fish is.

The swim bladder also may be used to adjust to the changing water pressure as the fish moves to different depths. In deeper water, the gas pressure in the swim bladder will be greater than it is in shallower water. If a fish at a great depth is suddenly brought to the surface, the large pressure in the swim bladder can force some of the internal organs of the fish out of its mouth.

(3) Submarines

Like steel ships, submarines have air spaces in them that make their relative densities less than that of water. However, submarines differ from steel ships in that they can move below the surface of the water. A submarine has tanks called ballast tanks which can be filled with water. When the submarine is to go under water, water is allowed to enter the ballast tanks so that the relative density of the submarine is close to that of the water which it is in. Use of diving rudders allows the submarine to dive to the desired depth. In order to reach the surface again, the water is forced out of the ballast tanks using compressed air, making the relative density less than that of water, and the submarine rises.

(4) Hot Air Balloons

A hot air balloon may seem like a strange thing to include in this section, but remember that buoyancy occurs in fluids, and fluids include gases and liquids. In a hot air balloon, air is heated and rises into the balloon through an opening at the bottom. The air is heated by a flame from a burner (which often uses propane). The balloon, the basket (which carries the passengers and equipment) and its contents initially have an average density greater than that of air. However, as heated air fills the balloon, the average density becomes less than that of air, and the balloon rises. This happens because warmer air has a lower density than cooler air. The height of the balloon can be adjusted by controlling the length of time that the flame is on. By allowing the air in the balloon to gradually cool, the balloon can have a controlled (and perhaps gentle) landing.

Do the following exercises and send them in for correction.

QUESTIONS

1. When suspended in air, a lead sinker has a weight of 1.72×10^{-1} N. When suspended in water, it has a weight of 1.56×10^{-1} N. If when suspended in a liquid, its weight is 1.40×10^{-1} N what is the relative density of the liquid?

2. Explain why the scale shown on the hydrometer float illustrated on page 22 has smaller numbers at the top and larger numbers at the bottom.

3. Why do steel ships float?

. A calibrated wooden stick is placed in water, and sinks to a depth of 2.5×10^{-1} m. To what depth would it sink in mercury?

5. What does the Plimsoll line indicate about the density of tropical salt water as compared to tropical fresh water? Explain your answer in terms of what happens when a ship has equal loads in the two kinds of water.

Lesson Summary

The following major topics were covered in this lesson.

1. How Archimedes' may have solved the problem of King Hieron's crown.

2. Density is defined as mass per unit volume.

$$D = \frac{m}{V}$$

Relative density is a comparison of the density of a substance (D_S) to the density of water (D_W).

$$d_R = \frac{D_S}{D_W}$$

3. Buoyancy causes bodies in fluids to have an apparent loss of weight.

4. Archimedes' Principle states that the loss of weight of an object immersed in a fluid is equal to the weight of the fluid it displaces.

5. Relative density may be measured by a number of devices, including the relative density bottle (pycnometer) and the hydrometer.

6. Applications of buoyancy and Archimedes' Principle can be observed in steel ships, submarines, fish, and balloons, as well as numerous other things.

END OF LESSON 11B

LESSON RECORD FORM

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1. BEFORE MAILING YOUR LESSONS, PLEASE SEE THAT:

(1) All pages are numbered and in order, and no paper clips or staples are used.
(2) All exercises are completed. If not, explain why.
(3) Your work has been re-read to ensure accuracy in spelling and lesson details.
(4) The Lesson Record Form is filled out and the correct lesson label is attached.
(5) This mailing sheet is placed on the lesson.

2. POSTAGE REGULATIONS

Do **not** enclose letters with lessons.

Send all letters in a separate envelope.

3. POSTAGE RATES

First Class

Take your lesson to the Post Office and have it weighed. Attach sufficient postage and a green first-class sticker to the front of the envelope, and seal the envelope. Correspondence lessons will travel faster if first-class postage is used.

Try to mail each lesson as soon as it has been completed.

When you register for correspondence courses, you are expected to send lessons for correction regularly. Avoid sending more than two or three lessons in one subject at the same time.

HYDRAULIC MACHINES

Many tedious tasks are today simplified because the hidden hand of hydraulics is doing the work. Cars are lifted with hydraulic jacks and hoists. Dentists and barbers use hydraulics to lift their chairs. Hydraulic brakes are standard equipment on cars. In the construction field hydraulic power is used to operate large earthmovers and cranes. Aircraft contain a network of hydraulic lines and components to power wheel brakes, landing flaps, air brakes and retractible landing gear. Some of the advantages of hydraulic powering over mechanical or electrical are:

1. The amount of power that can be handled is almost unlimited.
2. Easy, quick speed adjustment is possible over a large range while the energy source operates at constant speed.
3. There is smooth, rapid application and reduction of power.
4. There is complete control over torque and power.
5. There is a natural cushioning effect to reduce shock loads.
6. There is a smooth reverse mode.
7. Systems are relatively compact, long-lasting and safe. There are fewer moving parts than in mechanical systems and less danger of electrocution than in electrical systems.

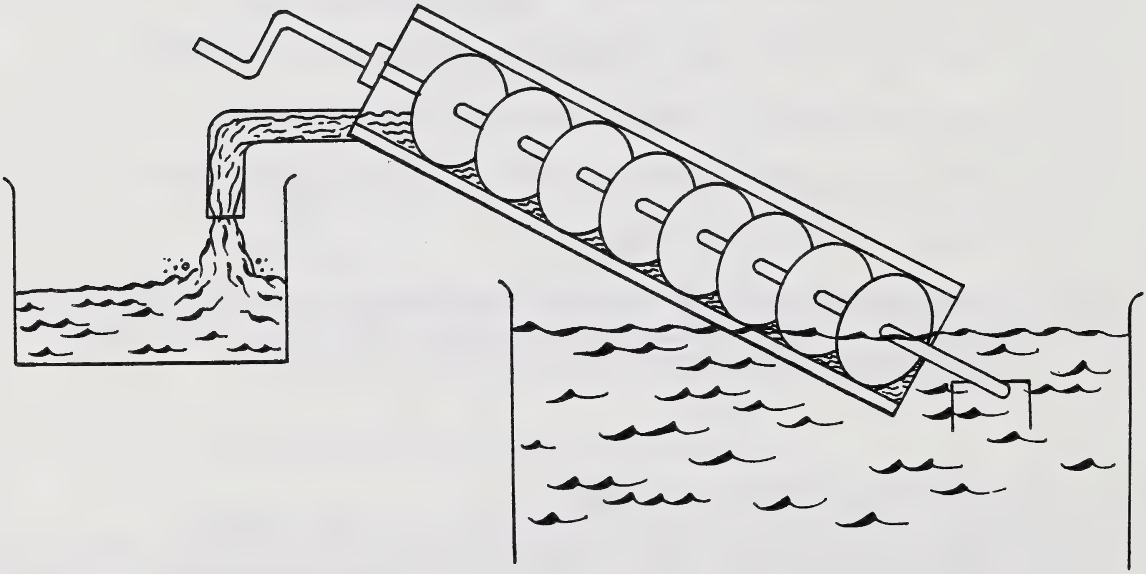
Principles and History of Hydraulics

Hydraulics, as we will consider it in this course, is the science of transmitting a force or motion through a confined liquid. This is actually a very narrow image, because in reality, hydraulics encompasses any study of fluids in motion.

The foundations of hydraulics originated many thousands of years ago. Ancient water works and irrigation systems were based on hydraulic principles. The name "hydraulics" itself originated with the Greek "hydros" which means "water".

Just prior to what is known as the Christian era, Archimedes described a device that would pump water. There is some controversy as to whether Archimedes was the inventor of this machine or whether he borrowed the idea from the Egyptians.

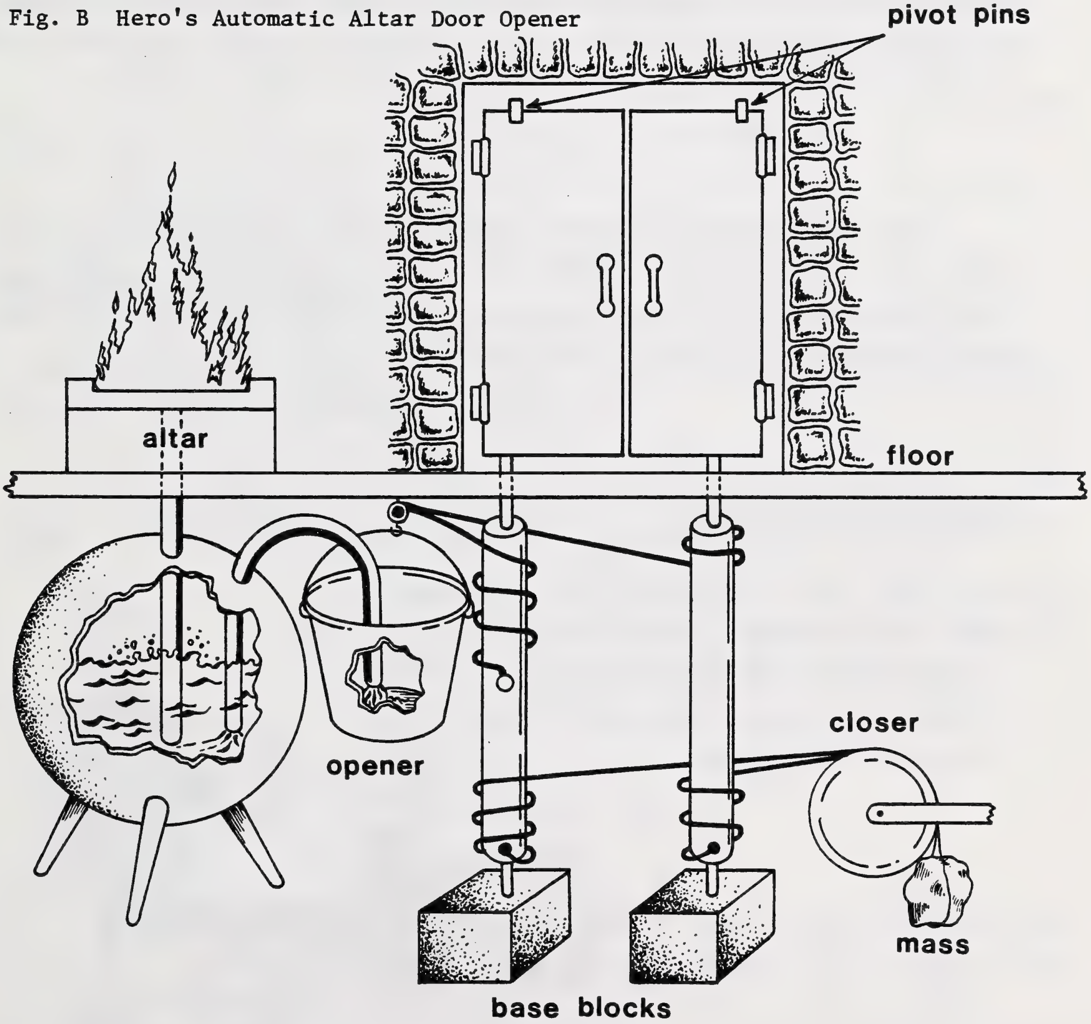
Fig. A –Archimedes Screw



At about this same time, Hero of Alexandria built his first turbine to harness the power of a moving liquid as depicted in Fig. B.

Shortly after this, Hero developed his steam turbine but it was not actually used for any practical purpose. However, the water wheel which is also a form of turbine, probably dates back as much as five or six thousand years in ancient China and Egypt.

Fig. B Hero's Automatic Altar Door Opener



When the fire is lit in the altar, water in the storage tank is heated and forced out into the pail to open the doors. The pail is sealed. (No leakage)

When the fire is out, the water is drawn back into the large container and the mass of the closer pulls the doors shut.

Yet, the actual transmission of power through pressure in a confined fluid has only been developed in recent times. In the days of Leonardo da Vinci (late 14th century) the concept of pressure was unknown. Even though da Vinci suggested several designs for hydraulic machinery, he failed to develop the understanding of pressure.

More than 100 years later in the 16th century, an Italian, Evangelista Torricelli observed the principle of the mercury barometer and related it to the weight of the atmosphere. It was, however, the French scientist Blaise Pascal who first discovered the principle of hydraulic leverage, known today as Pascal's Law. It is from this law that the entire science of pressure hydraulics has developed in a few hundred years.

* * *

The questions and problems for this lesson are all together at the end of the lesson. At this point you should be equipped to answer the questions in Exercise A, page 17. You may answer them now or you may choose to answer the questions for the whole lesson at once when you have studied all the lesson material.

* * *

Pascal's Principle

Pascal stated in 1650 that when any part of a confined liquid is subjected to pressure, the pressure is transmitted equally and undiminished to every portion of the inner surface of the containing vessel.

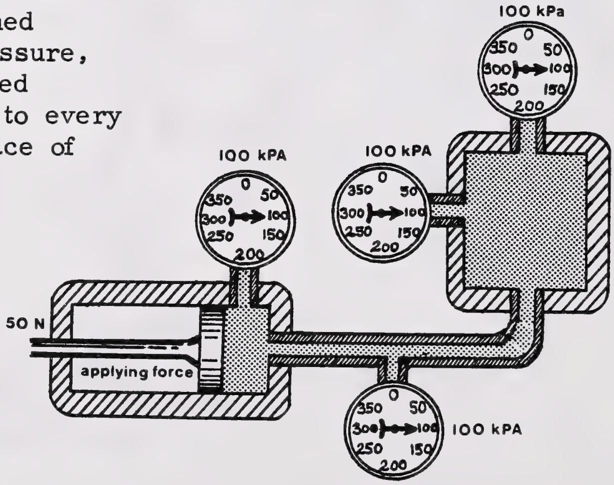
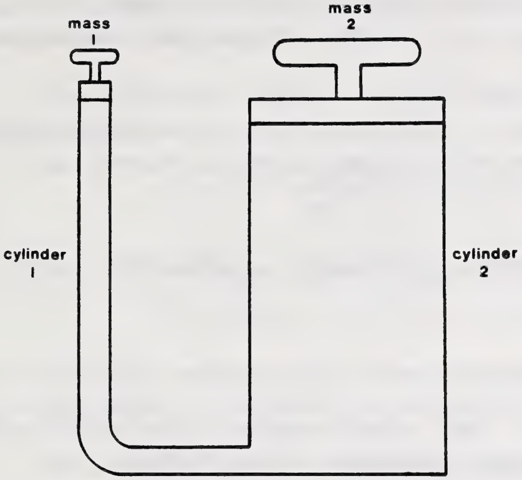


Fig. C If a liquid is completely enclosed and subjected to an outside force, the pressure is increased equally in all parts of the liquid.

Fig. D



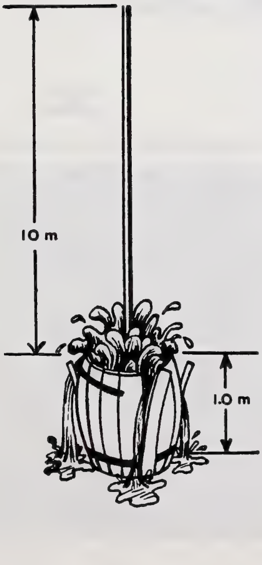
The apparatus Pascal used to develop his law probably consisted of two cylinders of different diameters with liquid trapped in them as in Fig. D. This system proves that leverage can be obtained hydraulically as well as mechanically. It can be shown that a small weight on a small piston can balance a larger weight on a larger piston provided the piston areas are in proportion to the weights.

The Hydrostatic Paradox

Imagine 0.500 m^3 of water. You would think that adding a mere 0.005 m^3 of water would increase the water pressure a relatively small amount. This is not always the case.

Consider that the 0.500 m^3 of water just fits into a barrel. A tight lid is put on the barrel and a pipe inserted into it. When the pipe is filled with 0.005 m^3 of water the added pressure bursts the barrel.

Fig. E



To understand this, consider a point directly below the pipe on the bottom of the barrel. First calculate the pressure when there is no water in the pipe.

$$\begin{aligned} P &= hDa_g \\ &= 1.0\ \text{m} \times 1.0 \times 10^3\ \text{kg/m}^3 \times 9.8\ \text{m/s}^2 \\ &= 9.8 \times 10^3\ \text{Pa} \\ &= 9.8\ \text{kPa}. \end{aligned}$$

Now calculate the pressure when the pipe is full. The water over the spot on the bottom of the barrel is now 11.0 m deep.

$$\begin{aligned} P &= hDa_g \\ &= 11.0\ \text{m} \times 1.0 \times 10^3\ \text{kg/m}^3 \times 9.8\ \text{m/s}^2 \\ &= 107\ 800\ \text{Pa} \\ &= 1.1 \times 10^2\ \text{kPa} \end{aligned}$$

The amazing conclusion is that adding 0.005 m^3 of water to the 0.500 m^3 already present, makes the pressure more than ten times as great.

The pressure actually added to the barrel by the water in the pipe is calculated by using the height of the pipe above the barrel as h.

$$\begin{aligned} P &= hDa_g \\ &= 10\ \text{m} \times 1.0 \times 10^3\ \text{kg/m}^3 \times 9.8\ \text{m/s}^2 \\ &= 9.8 \times 10^4\ \text{Pa} \\ &= 9.8 \times 10^1\ \text{kPa} \end{aligned}$$

According to Pascal's principle, this added pressure due to the water in the pipe is transmitted to all inner surfaces of the barrel.

Don't misunderstand. The pressure is not the same everywhere inside the barrel. But the ADDED pressure is added everywhere.

The sides of the barrel cannot withstand this added pressure and the barrel bursts.

* * *

You can now complete Exercise B, page 17

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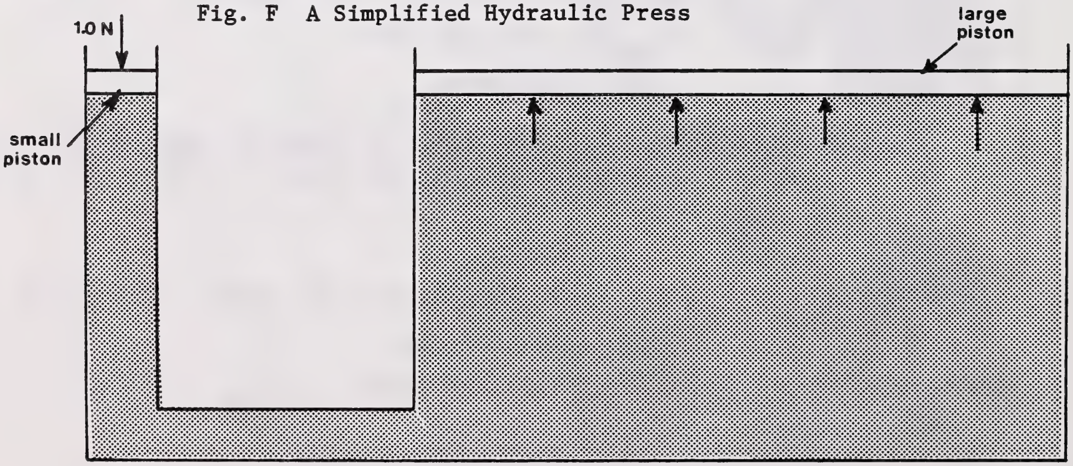
The Hydraulic Press

The significance of Pascal's principle is that a liquid can be used to increase force in a hydraulic machine.

Fig. F A Simplified Hydraulic Press



Say that the area of the small piston in Fig. F is 1.0 m^2. The area of the large piston is 10.0 m^2.

The pressure exerted on the small piston by the 1.0 N force is calculated:

$$P = \frac{F}{A} = \frac{1.0\ \text{N}}{1.0\ \text{m}^2} = 1.0\ \text{Pa}$$

But this pressure is transmitted undiminished to the large piston where

$$F = PA = 1.0\ \text{Pa} \times 10.0\ \text{m}^2 = 10\ \text{N}$$

So an object weighing 10 N and sitting on the large piston could be moved by applying a 1.0 N force to the small piston.

What's the catch? Something must be lost to pay for this increase in force. The answer comes from the fact that energy is conserved, or input work equals output work, in an ideal machine.*

The formula for calculating work is $W = Fd$. The work done in Joules equals the force applied in newtons times the distance through which the force acts in metres.

If input work (the work done on the small piston) W_{small} equals output work (the work done by the large piston) W_{large}

$$F_{small}d_{small} = F_{large}d_{large}$$

If the force exerted on the large piston is 10 times as large as the force on the small piston, the large piston will move only 1/10 the distance.

---

*NOTE: All machines discussed in this lesson are ideal. An ideal machine is a theoretical one that is 100% efficient. Any real machine uses up a good part of its energy to overcome friction, air resistance, etc. If a machine used 2500 J of energy to do 2000 J of work its efficiency is

$$\frac{\text{work output}}{\text{work input}} \times 100\% = \frac{2000\ \text{J}}{2500\ \text{J}} \times 100\% = 80\%$$

EXAMPLE 1

The pistons of an ideal hydraulic press have areas of 5.0 m^2 and 2.0×10^2 m^2. If a force of 1.0×10^2 N is supplied to the smaller piston:

(a) What is the pressure on the smaller piston?
(b) What is the pressure on the larger piston?
(c) What force can be exerted by the larger piston?
(d) If the smaller piston moves 0.50 m how far will the larger one move?

Given:
$A_{small} = 5.0\ m^2$
$A_{large} = 2.0 \times 10^2\ m^2$
$F_{small} = 1.0 \times 10^2\ N$
$d_{small} = 0.50\ m$

To find:
P_{small}
P_{large}
F_{large}
d_{large}

Solution: (a) $P = \frac{F}{A}$

$$P_{small} = \frac{F_{small}}{A_{small}}$$

$$= \frac{1.0 \times 10^2\ N}{5.0\ m^2}$$

$$= 2.0 \times 10^1\ Pa$$

(b) $*P_{large} = P_{small} = 2.0 \times 10^1\ Pa$

(c) $F_{large} = P_{large} A_{large}$

$$= 2.0 \times 10^1\ Pa \times 2.0 \times 10^2\ m^2$$

$$= 4.0 \times 10^3\ N$$

(d) $W = Fd$

$$W_{small} = F_{small}d_{small}$$

$$= 1.0 \times 10^{2} \text{ N} \times 0.50 \text{ m}$$

$$= 5.0 \times 10^{1} \text{ J}$$

$$*W_{large} = W_{small} = 5.0 \times 10^{1} \text{ J}$$

$$d_{large} = \frac{W_{large}}{F_{large}}$$

$$= \frac{5.0 \times 10^{1} \text{ J}}{4.0 \times 10^{3} \text{ N}}$$

$$= 1.2 \times 10^{-2} \text{ m}$$

* These are the important facts to remember about the hydraulic press. The pressure exerted by the small piston equals the pressure exerted on the large piston and the work done by the two pistons is equal.

* * *

You can now complete Exercise C, page 18

* * *

From Pascal to Hydraulics Today

The first practical use of pressure hydraulics was by Joseph Bramah in his 1795 press. This press used water as its fluid and, using Pascal's principle, achieved a huge mechanical advantage otherwise unattainable. But not until about 1850 did fluid power become prominent in technology. It was used to power presses, cranes, winches and extruding machines in Great Britain during the Industrial Revolution. In fact, by the late 1860's larger cities had central industrial hydraulic distribution systems in which large steam engines drove hydraulic water pumps to deliver water at fairly high pressures through pipes to factories for powering their machines.

But in the late 1800's the emergence of electricity caused hydraulic power to be overshadowed, until the 1900's when it became apparent that hydraulic power was superior in certain situations. In 1906 a hydraulic system for raising and lowering guns on battleships was developed, using oil rather than water as the fluid. In 1926, the United States developed the Direct Hydraulic System which had the pump, controls and actuator in a self-contained unit right on the machine using it.

In recent years the applications of fluid power have become almost limitless. A few of the more common and simple applications are illustrated following. The principles of the hydraulic press are discussed on pages 6 to 9.

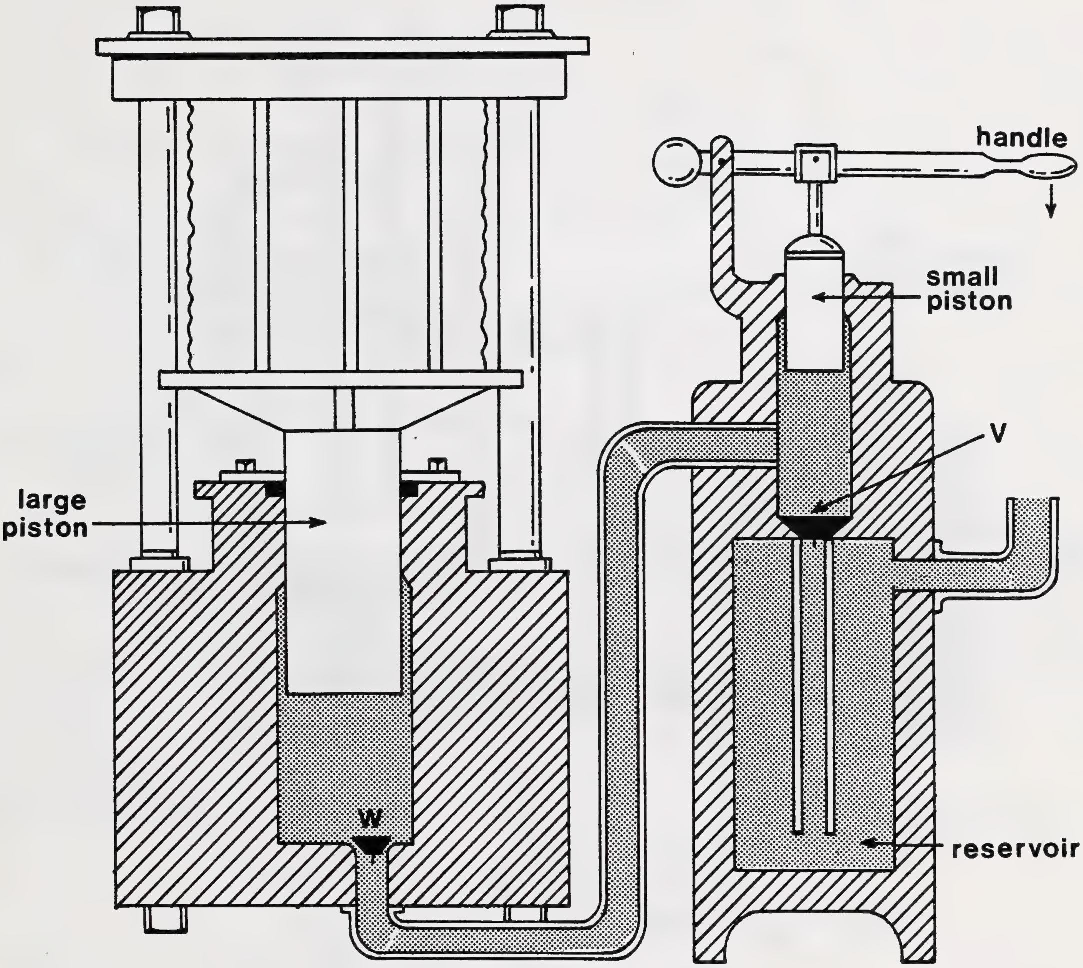
As may have become apparent to you by now, in any ideal hydraulic machine the ratio of the input and output forces is directly proportional to the ratio of the areas of the two pistons:

$$\boxed{\frac{\text{area of large piston}}{\text{area of small piston}} = \frac{\text{output force}}{\text{input force}}} \quad *$$

* Except for a hydraulic hoist as discussed on page 13.

Commercial Hydraulic Press

Fig. G

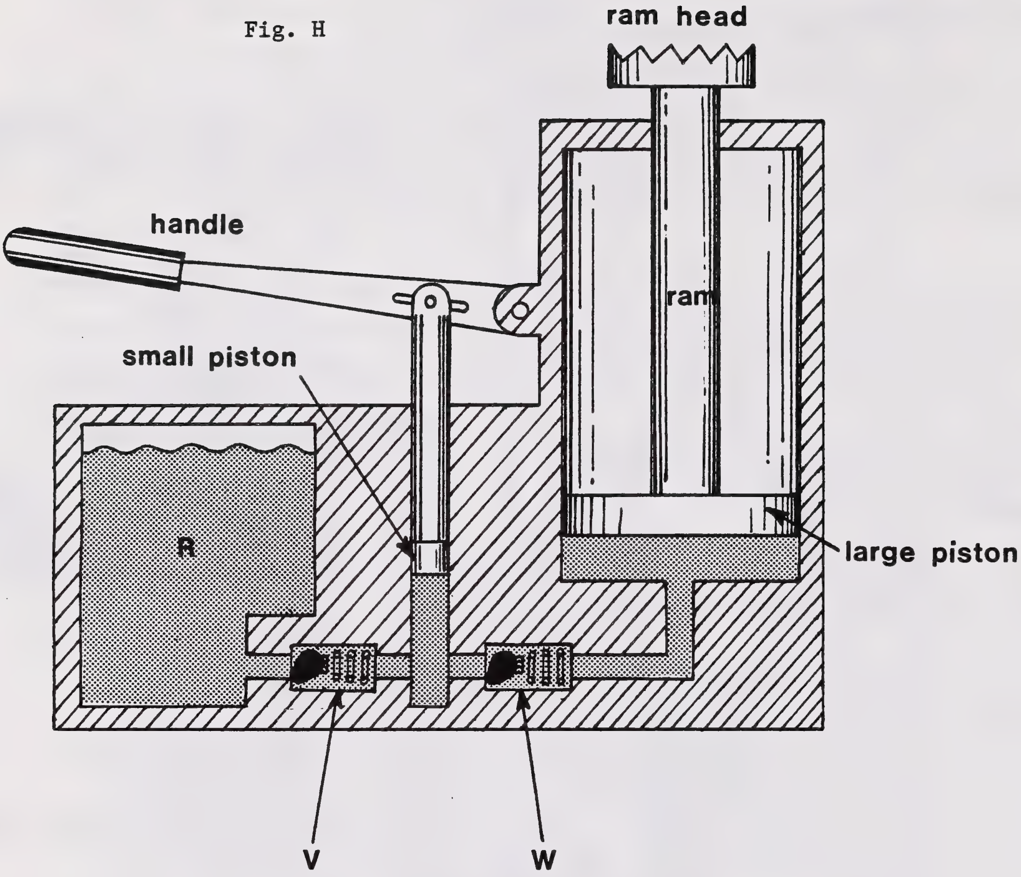


On the up stroke of the small piston, which acts as a pump to create a vacuum, valve v opens to admit oil from the reservoir. On the down stroke oil is forced past the check valve w and pushes up on the large piston.

Applications: Book binding, oil extraction from seeds, cotton and paper baling, shaping sheet steel for car bodies, etc.

Hydraulic Jack

Fig. H

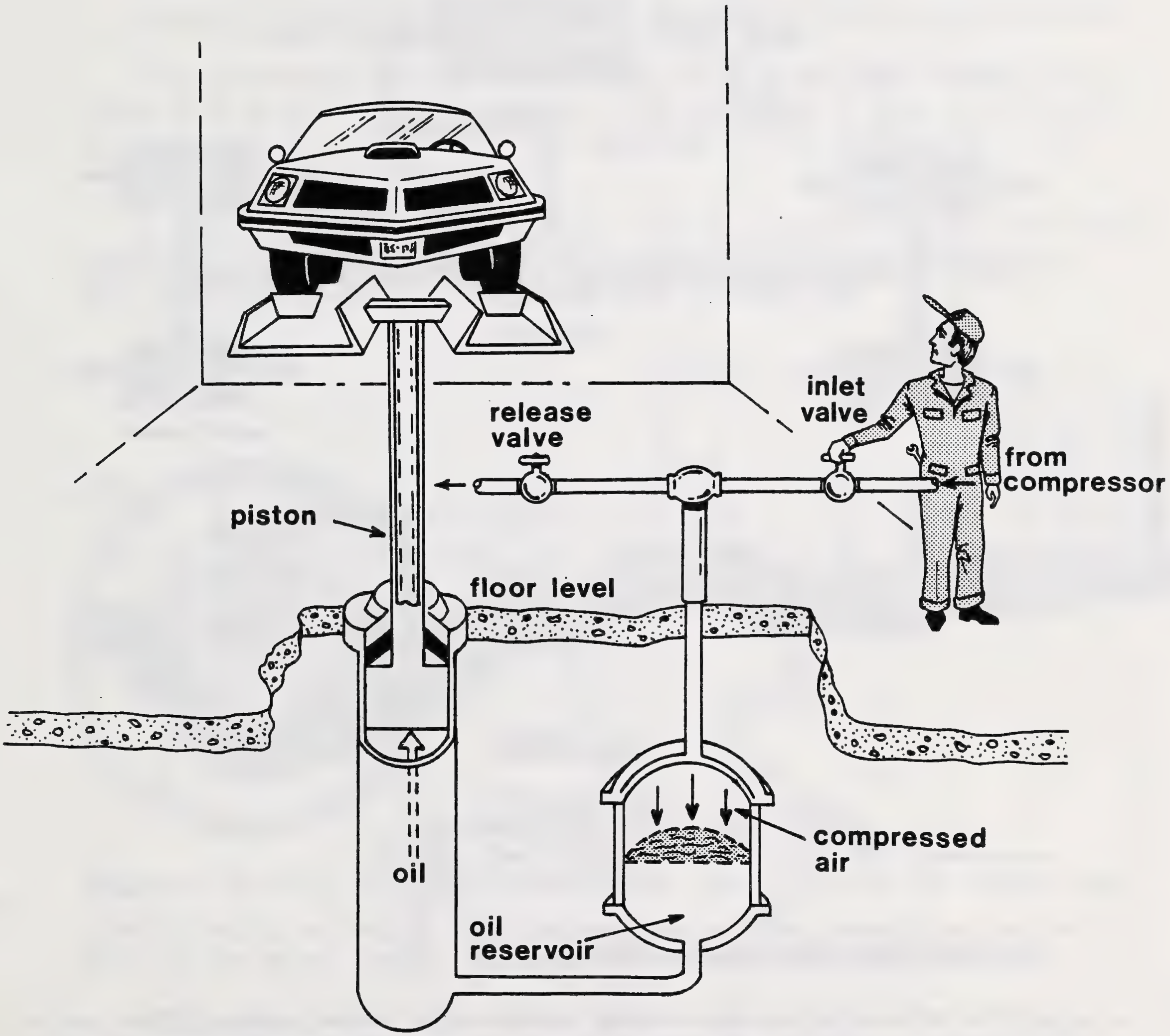


The principles are the same as for the hydraulic press in Fig. G.

If the large piston is 100 times larger than the small piston, a person exerting a 50 N force will be able to lift a 5000 N object with the ram head. Hydraulic jacks are used to lift buildings as well as vehicles.

Hydraulic Hoist

Fig. I



In this case pressure is applied to a large piston and transmitted to a smaller one. There is a loss in force but a gain in distance. Compressed air is able to supply the necessary force.

Since the input force is applied to the large piston, in this case

$$\frac{\text{area of large piston}}{\text{area of small piston}} = \frac{\text{input force}}{\text{output force}}$$

Hydraulic Brake System

Fig. J

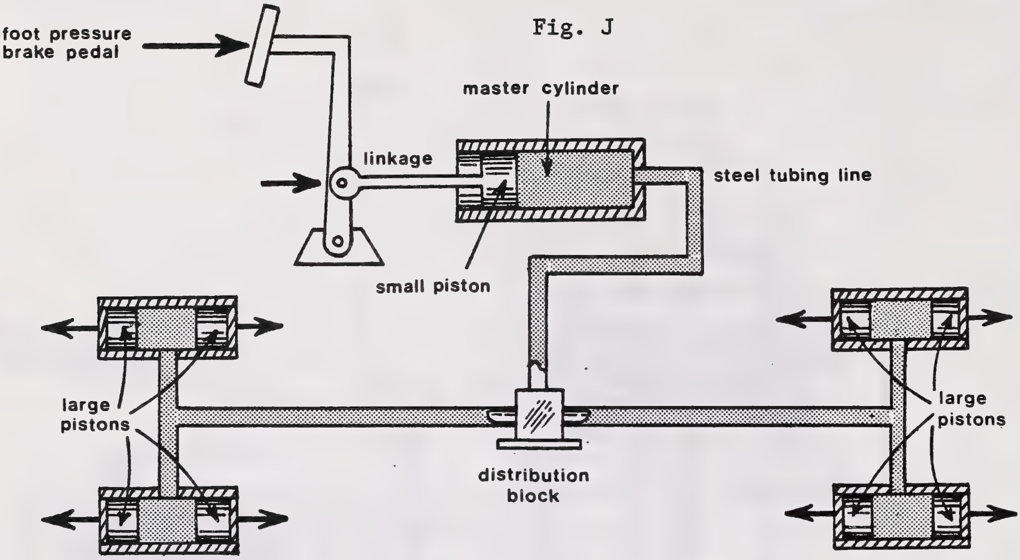
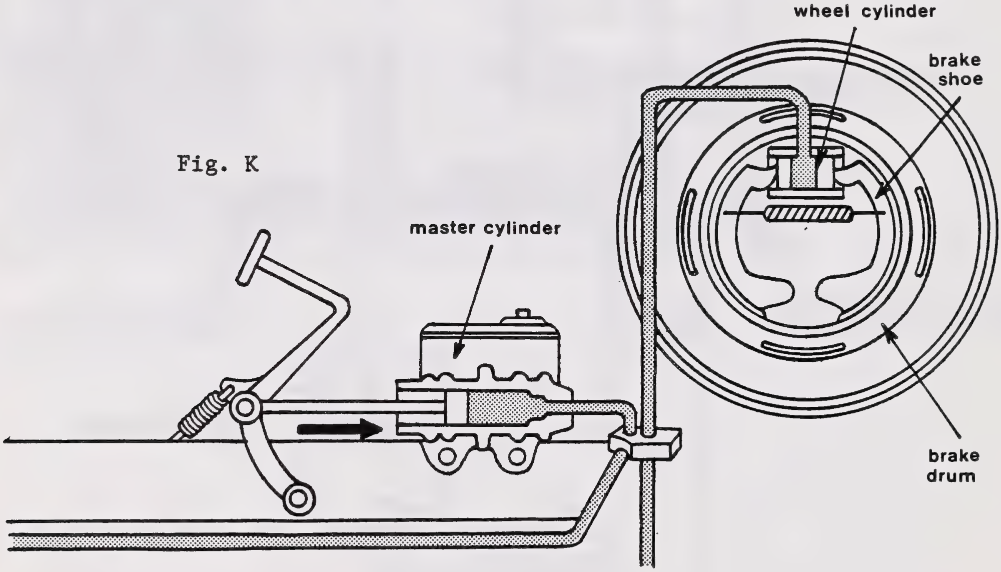


Fig. K



The driver of the automobile presses the brake pedal. This applies a pressure to the small piston which is transmitted undiminished to all large pistons. This causes the brake shoes to engage the drum and the car will stop.

* * *

You can now complete Exercise D, page 21

* * *

Water Pressure in Homes

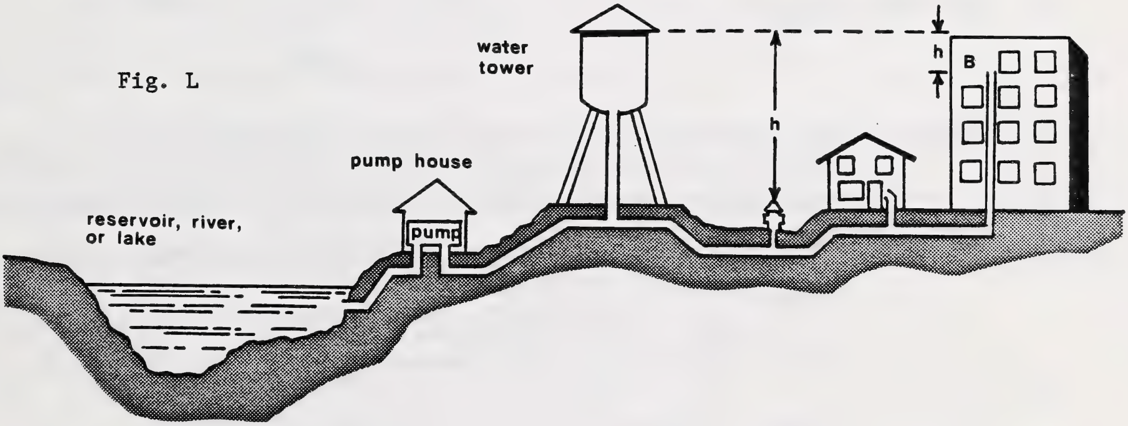
Remember that near the start of this lesson we said that hydraulics is the science of transmitting a force or motion through a confined liquid.

Another product of this science is the modern water supply system.

The occasional town is lucky enough to have its water supply high above it in a mountain lake nearby. The pressure in taps in that place is caused by the conversion of the potential energy of the water in the lake with respect to the tap.

In most places however, nature is not so cooperative and water must be pumped into huge elevated storage tanks or pressure tanks. See Fig. L for an illustration of the elevated storage tank.

Fig. L



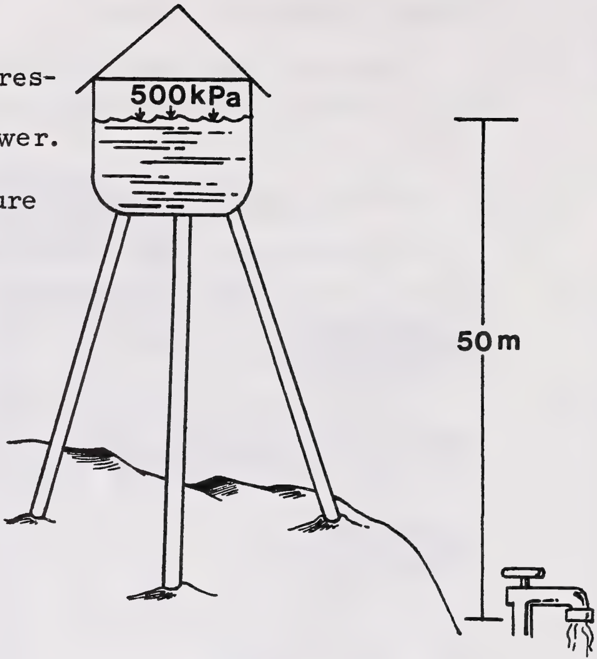
Pressure to a tap is somewhat less than hda_g because of internal pipe friction but it is obvious that the pressure will be greater on the main floor of the house than on the top floor of the high-rise building.

Engineers use the term water head to refer to the vertical distance of the water surface above the point in question.

A sealed pressure tank is often used in conjunction with the above type of system or in a small operation far away from a major system. As water is pumped into the tank, the air trapped inside is compressed to provide pressure for the system. The pump automatically keeps the water at a certain level so the pressure is constant.

EXAMPLE 2

Neglecting friction, calculate the pressure in a tap 5.0 × 10 m below the water surface in the town water tower. There is compressed air above the water in the tank exerting a pressure of 5.0×10^2 kPa. Remember the mass density of water is 1.0×10^3 kg/m³.



Given:
$h = 50$ m
$d = 10 \times 10^3$ kg/m³
$a_g = 9.8$ m/s²
$P_{air} = 5.0 \times 10^2$ kPa

To find: P_{total}

Solution: The pressure of the water in the tap depends on two things. First, according to Pascal's principle, the pressure due to the compressed air in the water tower, P_{air}, will be transmitted throughout the liquid without loss and of course a pressure, P_{water}, due to the height of the column of water above the tap, to the tower, will be exerted. The total pressure will be equal to the sum of these two pressures. $P_{total} = P_{air} + P_{water}$.

$$\begin{aligned} P_{water} &= hda_g \\ &= 50 \text{ m} \times 1.0 \times 10^3 \text{ kg/m}^3. \times 9.8 \text{ m/s}^2 \\ &= 4.9 \times 10^5 \text{ Pa} \\ &= 4.9 \times 10^2 \text{ kPa} \end{aligned}$$

$$\begin{aligned} P_{total} &= P_{air} + P_{water} \\ &= 5.0 \times 10^2 \text{ kPa} + 4.9 \times 10^2 \text{ kP} \\ &= 9.9 \times 10^2 \text{ kPa} \end{aligned}$$

The pressure in the tap is 9.9×10^2 kPa.

* * *

You can now complete Exercise E, page 24.

* * *

Since pages 1 to 16 of this lesson contain no exercises to be submitted for correction it is necessary to mail in only pages 17 to 25.

EXERCISE A

1. Define hydraulics: ______

2. Give what you consider to be the three main advantages of hydraulic power over other types of power.

3. Name three ancient uses of hydraulics.

EXERCISE B

1. State Pascal's principle which is the cornerstone of hydraulic principles.

2. In your own words, explain the hydrostatic paradox.

____

____

____

____

____

3. Who solved this paradox? __________________________

EXERCISE C

1. What is the significance of Pascal's principle?

____

____

____

2. What is lost to make up for the huge magnification of force possible with a hydraulic machine?

____

____

3. What two things concerning the large and small pistons of a hydraulic machine are equal?

____

____

____

____

4. At 7.0 m high container can withstand 50.0 kPa of pressure. It is filled with gasoline (mass density 7.0×10^2 kg/m^3)

Someone who had nothing better to do put a tight lid with a hole in it on the container. He then inserted a pipe in the hole and filled it with gasoline. The pipe extended 1.0 m above the top of the container. Will the container burst? Show all of your calculations.

5. 5.0×10^2 N of force are applied to a 4.5×10^{-2} m^2 piston of a hydraulic press.

(a) What is the pressure on this piston?

(b) If the large piston has an area of 27.0 m^2 what force can it exert?

(c) If the small piston moves 3.0 m while exerting the force, how far does the large piston move?

1. What is unusual about the hydraulic hoist? Why is this?

2. Hydraulic brakes are standard equipment on cars today. Briefly explain how they work.

3. An ideal hydraulic jack has a small piston of RADIUS 2.5 cm and a large piston of RADIUS 1.0×10^2 cm. If a boy can exert 200 N of force, what is the heaviest object he can lift with the jack? (Remember that the area of a circle is calculated by $A = \pi r^2$)

4. (a) The pistons in a hydraulic hoist have areas of $1.0\ m^2$ and $4.0\ m^2$. What is the force necessary to lift an 8 t vehicle? (See page 13) Note that 8.0 t refers to mass, not force.

(b) If the vehicle is raised 3.0 m, how far did the other piston move?

5. 2000 kPa of pressure is developed in the master cylinder of a car's brake system. What is the pressure delivered

(a) to each of the front brakes?

____

____

(b) to each of the rear brakes?

____

____

EXERCISE E

1. List 3 possible sources of pressure in a household faucet.

2. Why is the pressure in a real tap less than in an ideal situation?

3. A trailer has a pressurized water system. If the pressure of the air in the tank is 2.5×10^2 kPa, what is the pressure in a tap at the same elevation as the tank, neglecting friction? What scientific law do you use to answer this question?

4. The water pressure of a tap 100 m below the surface of water in the town water tower is 1.5×10^3 kPa. Calculate the pressure due to compressed air above the water in the tank.

Lesson Summary

The following major concepts were discussed in Lesson 12B.

1. Hydraulic power has many advantages over other sorts of power.
2. Hydraulics is the branch of physics concerning the transmission of a force or motion through a confined liquid.
3. Hydraulic power was used thousands of years ago.
4. Many scientists added knowledge to the field of hydraulics but Pascal's principle was most instrumental in the development of modern hydraulic technology.
5. Pascal stated that an external pressure applied to a confined liquid is transmitted equally and undiminished throughout the liquid.
6. Pascal's principle, applied to a hydraulic machine makes possible an increase in force. Since the pressure applied to the small piston is transmitted to the large piston undiminished

   $$P_{small} = P_{large} \quad \text{or} \quad \frac{F_{small}}{A_{small}} = \frac{F_{large}}{A_{large}}$$

7. Also in a hydraulic machine the work done on the small piston equals the work done by the large piston. Since $W = Fd$ this means

   $$F_{small}d_{small} = F_{large}d_{large}$$

   So if the force is increased for the large piston, the distance moved is decreased.

8. In a hydraulic machine

   $$\frac{\text{area of large piston}}{\text{area of small piston}} = \frac{\text{output force}}{\text{input force}}$$ (except for the hydraulic hoist)

9. Examples of hydraulic machines to which the above concepts apply are the hydraulic press, jack, hoist and hydraulic brakes.

END OF LESSON 12B

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